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Presentation

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Selected Tether Applications in Space

An Analysis of Five Selected Concepts

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MARTIN MARIETTA

SELECTED TETHER APPLICATIONS IN SPACE

AN ANALYSIS OF FIVE SELECTED CONCEPTS

FINAL REPORT/PRESENTATION

CONTRACT NAS 8-35499

MARSHALL SPACE FLIGHT CENTER

JULY 31, 1984

- o SELECT CONCEPT.
- o DEFINE A SPECIFIC MISSION TO BE PERFORMED.
- o ESTABLISH GROUNDRULES AND ASSUMPTIONS AS REQUIRED TO DEFINITIZE THE CONCEPT.
- o DEVELOP AN OPERATIONS SCENARIO.
- o PERFORM ANALYSES AS REQUIRED:
  - DEVELOP ORBIT CONSIDERATIONS
  - IDENTIFY EQUIPMENT/FUNCTIONAL REQUIREMENTS
  - TETHER DYNAMICS.
- o EQUIPMENT CONCEPTS.
- o SAFETY.
- o IDENTIFY AREAS OF UNCERTAINTY.
- o TECHNOLOGY DEVELOPMENT NEEDS.

A - TETHER EFFECTED SEPARATION OF AN EARTH BOUND SHUTTLE FROM THE SPACE STATION.

B - TETHER EFFECTED ORBIT BOOST OF A SPACECRAFT (AXAF) INTO ITS OPERATIONAL ORBIT FROM THE SHUTTLE.

C - AN OPERATIONAL SCIENCE/TECHNOLOGY PLATFORM TETHER DEPLOYED FROM SPACE STATION.

D - TETHER MEDIATED RENDEZVOUS - AN OMV TETHER DEPLOYED FROM SPACE STATION TO RENDEZVOUS WITH AN AERO-BRAKED OTV RETURNING FROM A PAYLOAD DELIVERY MISSION TO GEOSYNCHRONOUS ORBIT.

E - AN ELECTRODYNAMIC TETHER USED IN A DUAL MOTOR/GENERATOR MODE TO SERVE AS THE PRIMARY ENERGY STORAGE FACILITY FOR SPACE STATION.

EACH OF THESE CONCEPTS WILL BE DISCUSSED IN A SEPARATE SECTION DESIGNATED BY THE ABOVE LETTERS.

INTRODUCTION SECTION DESIGNATED BY I.

EACH LETTER SECTION WILL COMPRISE THE FOLLOWING NUMBERED HEADINGS:

1. X CONCEPT DEFINITION
2. X GROUNDRULES AND ASSUMPTIONS
3. X OPERATIONS CONCEPT
4. X ORBIT CONSIDERATIONS/DYNAMICS
5. X TETHER SYSTEM DESIGN CONSIDERATIONS
6. X TETHER DYNAMICS
7. X FUNCTIONAL REQUIREMENTS
8. X HARDWARE CONCEPTS
9. X SAFETY CONSIDERATIONS
10. X AREAS NEEDING FURTHER STUDY
11. X TECHNOLOGY DEVELOPMENT NEEDS
12. X ALTERNATIVE "CONVENTIONAL" CONCEPTS
13. X CONCLUSIONS AND RECOMMENDATIONS

SECTION A

TETHER EFFECTED SEPARATION OF AN EARTH BOUND SHUTTLE FROM THE SPACE STATION.

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Concept Definition

Since the departing Shuttle represents a large mass (typically, 190 klb or 86,200 kg) compared to the assumed Space Station mass of 300 klb (136,100 kg), it has been suggested as a likely candidate for momentum transfer operations with a tether. Also, the Shuttle will be a frequent visitor to the Space Station (at least 4 times per year for crew rotation plus many other delivery flights) and it will undoubtedly be the largest mass to dock with the station for many years after IOC.

As the tethered Orbiter is deployed downward from the Space Station, the angular momentum of the Orbiter is gradually decreased while that of the Space Station is increased. When the tether is released, the Orbiter descends to a lower orbit and the Space Station is boosted to a higher orbit.

The basic objectives of this approach are to reduce the OMS propellant required to effect Shuttle reentry, to reduce the propellant requirement for atmospheric drag makeup on the station, and to provide an angular momentum accumulation on the Space Station for potential tethered assisted launch operations to geosynchronous orbit.

- USE A TETHER TO EFFECT THE SEPARATION FROM THE SPACE STATION OF AN EARTH BOUND DEPARTING SHUTTLE.
- ANGULAR MOMENTUM WILL BE TRANSFERRED FROM THE SHUTTLE TO THE SPACE STATION BOOSTING IT INTO A HIGHER ORBIT.

<u>OBJECTIVES</u>

- REDUCE THE PROPELLANT REQUIRED TO EFFECT SHUTTLE RE-ENTRY.
- REDUCE PROPELLANT REQUIREMENT FOR ATMOSPHERIC DRAG MAKE UP ON STATION.
- PROVIDE ANGULAR MOMENTUM ACCUMULATION BY SPACE STATION FOR POTENTIAL TETHER MEDIATED LAUNCH OPERATIONS.

Ground Rules and Assumptions

The tether length shall be selected to assure that the Orbiter perigee does not drop below 100 nmi (185 km) after tether release. All calculations are based on an assumed Space Station mass of 300 klb (136,100 kg) and a departing Orbiter mass of 190 klb (86,200 kg).

The maximum time for deploying the tether downward and releasing the Orbiter is one 8 hr. crew shift. The maximum time for retrieving the tether and end effector is also one 8 hr. shift.

The Space Station is assumed to be in a 270 nmi (500 km) circular orbit at a 28.5 degree orbit inclination at initiation of tether deployment.

Attitude torques on the station, caused by tether operations, will be maintained near zero with a tether alignment device. Braking energy generated by tether deployment will be disposed of on the Space Station. In the event of tether failure or other emergency, the Space Station crew will be able to release the tether by guillotine. (The Orbiter crew will also have this capability).

The Space Station will track the end effector through all phases of tether operations with its on-board MW radar and also maintain a telemetry link with the end effector.

- o SELECT TETHER SEPARATION DISTANCE TO ASSURE A 100 NMI (185 KM) PERIGEE FOR THE ORBITER AFTER TETHER RELEASE.

PRIMARY MASSES

- o SPACE STATION MASS 300 KLB (136,100 KG)
- o RETURNING ORBITER MASS 190 KLB (86,200 KG)

DEPLOYMENT/RETRIEVAL

- o DEPLOY AND RELEASE ORBITER DOWNWARD WITHIN ONE 8 HR. SHIFT.
- o RETRIEVE TETHER AND END EFFECTOR WITHIN ONE 8 HR. SHIFT.

SPACE STATION CONSIDERATIONS

- o SPACE STATION IN 270 NMI (500 KM) CIRCULAR ORBIT AT 28.5 DEG. INCLINATION.
- o MAINTAIN ATTITUDE TORQUES INTO THE STATION NEAR-ZERO WITH A TETHER ALIGNMENT DEVICE.
- o BRAKING ENERGY GENERATED DURING TETHER DEPLOYMENT WILL BE DISPOSITIONED ON THE SPACE STATION.
  - ENERGY GENERATED = 5.57 X 10^8 JOULES
  - AVERAGE POWER FOR 8 HRS = 19.35 KW (26 HP)
  - PEAK POWER DURING PERIOD = 50 KW (67 HP)
- o EMERGENCY TETHER RELEASE BY GUILLOTINE CONTROLLED BY STATION CREW (DUE TO BREAK, ETC.).
- o SPACE STATION TRACKS AND EFFECTOR DURING DEPLOYMENT/RETRIEVAL WITH M.W. RADAR.
- o MAINTAIN A TELEMETRY LINK WITH THE END EFFECTOR.

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Ground Rules and Assumptions (Continued)

The required end effector shall be a device with a propulsion/attitude control system to provide 6 degree of freedom control during tether retrieval. (The presence of a mass is also expected to dampen tether motion after Orbiter release).

For safety reasons, sufficient OMS propellant will be carried to negotiate an untethered deorbit in the event of a tether failure. As experience is gained, an alternate approach might be taken which would involve off-loading a significant portion of this propellant (allowing more deliverable payload to the Space Station). The alternate mode would involve a return to the Space Station for more OMS propellant, in the event of an aborted tether deployment.

Standard release of the tether with end effector will be controlled by the Orbiter crew. In case of emergency, the Orbiter crew can instantly release the tether above the end effector with a guillotine. (Communication between the Orbiter crew and Space Station crew will be available throughout the deployment and release sequence).

END EFFECTOR REQUIREMENT

- AN END EFFECTOR DEVICE WITH A PROPULSION/ATTITUDE CONTROL SYSTEM FOR 6 DEGREE OF FREEDOM CONTROL DURING TETHER RETRIEVAL IS REQUIRED. THE END EFFECTOR MASS WILL ALSO DAMPEN TETHER MOTION AFTER ORBITER RELEASE.

ORBITER CONSIDERATIONS

- SUFFICIENT OMS PROPELLANT WILL BE CARRIED TO NEGOTIATE AN UNTETHERED DEORBIT FROM THE SPACE STATION IN CASE OF TETHER FAILURE DURING DEPLOYMENT.
- STANDARD RELEASE OF THE TETHER/END EFFECTOR IS CONTROLLED BY THE ORBITER CREW.
- EMERGENCY TETHER RELEASE, IN CASE OF TETHER FAILURE, IS CONTROLLED WITH A GUILLOTINE ABOVE THE END EFFECTOR BY THE ORBITER CREW. (THIS IS AN ADDITION TO THE INDEPENDENT TETHER RELEASE CAPABILITY BY THE SPACE STATION CREW IN THE EVENT OF TETHER FAILURE).

Operations Concept

Using the RMS (Space Station or Shuttle, as required) and EVA, the bridge beam will be installed on the available sill and keel fittings closest to the Orbiter CM. The bridge beam will be carried up in a stowed position and be installed after the return payloads are installed. After the bridge beam installation, the tether system end effector would be attached to the attachment/release device on the bridge beam, again utilizing RMS and EVA activity.

The Orbiter will then separate from the Space Station with RCS thrusting, carrying the tether along to a position approximately 250 m below the Space Station, in the nadir direction. The Orbiter would then adjust its attitude to direct the tether tension force through the CM. Simultaneously, the tether alignment device would direct the tether tension through the Space Station CM.

After this point, further deployment of the Shuttle would be controlled by the tether system operator using gravity gradient forces and controlled braking from the tether reel drive. At the specified tether length, deployment would cease and the Orbiter and tether would be stabilized along the nadir direction. The Orbiter crew would then initiate release at the appropriate time, close the cargo bay doors, and prepare for its reentry OMS burn at a later orbit apogee passage.

After tether release, the Space Station tether system operator would accomplish tether retrieval, capture and stow the end effector, and secure the tether system.

1. USING RMS (SS OR SHUTTLE) AND EVA, INSTALL BRIDGE BEAM IN SHUTTLE CARGO BAY.
2. USING RMS (SS OR SHUTTLE) AND EVA, ATTACH TETHER SYSTEM END EFFECTOR TO THE ATTACHMENT/RELEASE DEVICE ON THE SHUTTLE BRIDGE BEAM.
3. SEPARATE SHUTTLE FROM STATION.
4. USING SHUTTLE RCS, INITIATE SEPARATION MANEUVER FROM STATION PULLING TETHER ALONG.
5. CONTINUE RCS SEPARATION FROM STATION ALONG NADIR DIRECTION TO APPROXIMATELY 250M. ADJUST SHUTTLE ORIENTATION SUCH THAT TETHER TENSION FORCE IS DIRECTED THRU SHUTTLE CM.
6. SIMULTANEOUS WITH 5, THE TETHER ALIGNMENT DEVICE ADJUSTS TO DIRECT THE TETHER TENSION THRU THE SS CM.
7. AFTER THIS POINT FURTHER DEPLOYMENT OF THE SHUTTLE IS CONTROLLED BY THE TETHER SYSTEM OPERATOR USING GRAVITY GRADIENT FORCES, AND WITH CONTROLLED BRAKING FROM THE TETHER REEL DRIVE.
8. AT SPECIFIED DEPLOYMENT LENGTH STOP DEPLOYING AND STABILIZE.
9. ORBITER CREW INITIATES RELEASE AT SPECIFIED TIME.
10. ORBITER CLOSES CARGO BAY DOORS AND PREPARES FOR RE-ENTRY.
11. SS TETHER OPERATOR INITIATES TETHER RETRIEVAL.
12. CAPTURE AND STOW END EFFECTOR.
13. SECURE TETHER SYSTEM.

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Shuttle Deorbit Sequence/Space Station Response

When the tethered earth returning Orbiter, with its assumed mass of 190 klb (86,200 kg) leaves the Space Station, with its assumed mass of 300 klb (136,100 kg) a significant amount of angular momentum is transferred.

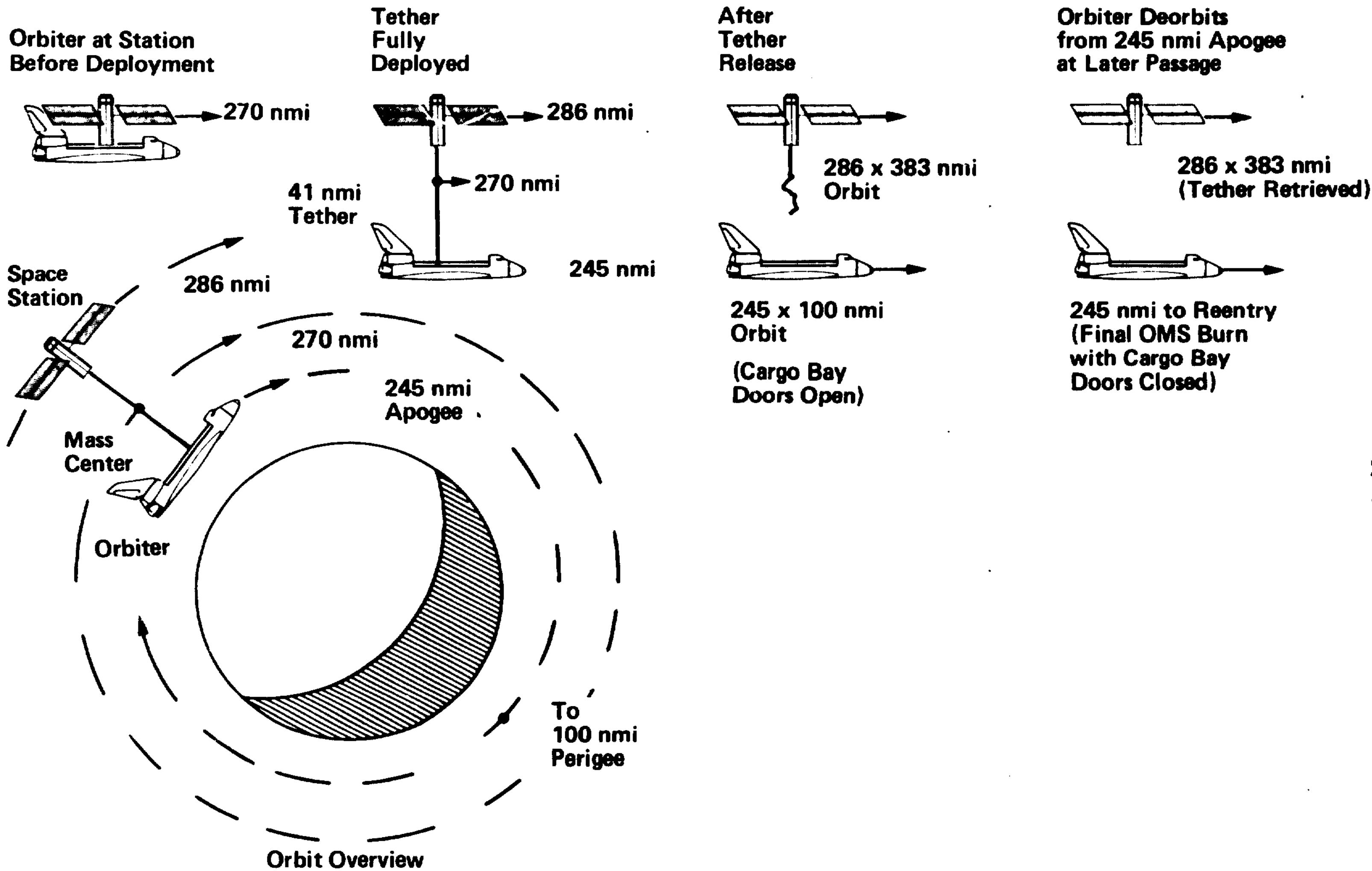
A tether length of 41 nmi (76 km) is selected to insure that when the Orbiter is released its low altitude point of 100 nmi (185 km) remains safely above reentry altitude to allow sufficient time to close the cargo bay doors and prepare for reentry.

As momentum is exchanged between the Space Station and the Shuttle during tether deployment, the center of mass remains at the original altitude of 270 nmi (500 km). The Space Station ascends to an altitude of 286 nmi (530 km) and the Shuttle descends to an altitude of 245 nmi (454 km) at the end of tether deployment.

When the tether is released at the Orbiter (zero libration angles and rates) the Orbiter will be at the apogee of a 245 nmi (454 km) by 100 nmi (185 km) orbit. It will remain in this orbit until a later apogee passage, when preparations for reentry are completed. At this time the final OMS burn will be made and the Orbiter will proceed to reentry and landing.

Simultaneously, with tether release, the Space Station will be at the perigee of a 286 nmi (530 km) by 383 nmi (709 km) orbit. As the station advances into its new orbit the tether and end effector will be retrieved and stowed. It is estimated that the Space Station could remain above its original orbit of 270 nmi (500 km) without orbit stationkeeping thrusting for 1 1/2 years to 7 years, depending upon the time of the 11 year solar cycle that this momentum transfer takes place. Conversely, a number of tether assisted payload launches to higher altitudes could be accomplished for a shorter period of time before the momentum "bank account" is depleted and another tethered STS deorbit is scheduled.

Shuttle Deorbit Sequence/Space Station Response



Tether System Design Considerations

The tether criteria shown are based on the orbit dynamics analysis which determines the length of tether. The tether length and the masses of the Station and Shuttle in turn determine the tether tension developed. Multiple reuse requires the protective teflon braid jacket. The design factor is an engineering judgment decision. The requirement for high modulus is to minimize the amount of elastic energy stored in the tether at release.

The tether selected to comply to the identified requirements is defined under "tether selection".

The tether reel size is 96 inches inside length and approximately 65 inches in diameter. These dimensions can be varied so long as the reel capacity remains adequate to hold the required length of tether.

The energy generated during the deployment is given by the integral of the tension over the length of the tether and is equal to the value shown. Approximately 15% of this energy will appear as joule heating in the braking motor/generator. The remainder will be electrical power which can either be used for some productive purpose on the station or else it must be rejected as waste heat by use of a dedicated high temperature radiator.

The average rate at which power is generated over the 8 hour deployment is 19.35 kW.

The actual peak values will depend on the reel/drive design and on the peak rates defined by the deployment damping control laws. For the design parameters used for this study, the peak power output level was 67 horsepower (50 kW).

- o TETHER CRITERIA
  - DEPLOYED LENGTH: 41 NMI (76 KM)
  - 5% RESERVE ON REEL: 2 NMI (3.8 KM)
  - DEPLOYED TENSION: 3300 LBF (14,700 N)
  - DESIGN FOR MULTIPLE REUSE (20X)
  - PROVIDE TEFLON BRAID JACKET (ABRASION, EROSION)
  - DESIGN FACTOR: 2.5 (OR BETTER)
  - USE HIGH MODULUS TO MINIMIZE STORED ELASTIC ENERGY
- o TETHER SELECTION
  - BRAIDED KEVLAR 49 (DUPONT ARAMID FIBER)
  - MODULUS 22.5 X 10^6 PSI
  - KEVLAR BRAID DIAMETER: 0.300 IN (7.6 MM)
  - JACKETED DIAMETER: 0.320 IN (8.1 MM)
  - BREAK STRENGTH 9000 LBF (39,600 N)
  - MASS/LENGTH 26.9 LBM/KFT (40 KG/KM)
  - TOTAL DEPLOYED MASS 6700 LBM (3040 KG)
  - STRAIN AT WORKING TENSION: 0.278%
  - ELONGATION UNDER TENSION: 690 FT (211 M)
  - DEFORMATION ENERGY: 1.14 X 10^6 FT-LB (0.43 KWH)
- o REEL/BRAKING DRIVE
  - REEL SIZE: LENGTH 96 IN (244 CM), DIAMETER 65 IN (165 CM)
  - ENERGY DEVELOPED: 4.11 X 10^8 FT-LB (155 KWH)
  - 8 HOUR AVERAGE: 26 HP (19.35 KW)
  - PEAK RATES: 67 HP (50 KW)
  - REJECT ENERGY AS WASTE HEAT THRU DEDICATED HIGH TEMPERATURE RADIATOR

(CONT'D)

Tether System Design Considerations (Continued)

Several methods of carrying out the release of the tether were considered. The motive was to reduce concern over the recoil behavior of the tether due to the elastic energy of the stretched tether.

One method considered was to attempt to release the tension just prior to release by suddenly driving the reel to deploy more tether at a rate high enough to both match the separation rate of the vehicles and to relive the tension. The required rates were judged to be unfeasible and the method rejected.

A second method considered was to use a secondary tether deployed from the end effector to act as a recoil damper. This method was rejected because of the problem of retrieving the secondary tether and the design complication of the end effects.

The third method and the one chosen for this analysis is to select a tether material with the highest available modulus in order to reduce the amount of elastically stored energy. See pages A-6.1 thru A-6.5 for further discussion based on simulation runs.

TETHER RELEASE CONCEPTS CONSIDERED

- o MATCH VEHICLE SEPARATION RATES WITH STATION REEL DRIVE
  PROBLEMS: 1) RELAXATION TIME OF TETHER (ORDER OF 8 SEC)
  2) VEHICLE SEPARATION RATES

- o USE A SECONDARY TETHER FOR RECOIL ATTENUATION OF MAIN TETHER (SECONDARY TETHER PART OF END EFFECTOR)
  PROBLEMS: 1) RETRIEVAL OF SECONDARY TETHER
  2) END EFFECTOR DESIGN COMPLICATION

- o DESIGN TETHER FOR ACCEPTABLE RECOIL CHARACTERISTICS

FOR THIS ANALYSIS IT HAS BEEN ASSUMED THAT AN ACCEPTABLE TETHER RECOIL CHARACTERISTIC WILL BE AVAILABLE.

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Tether Dynamics

Simulation runs of the tether deployment of the Orbiter using the TETHDY program indicates a straightforward deployment operation with no unusual angular excursions or tension anomalies.

The maximum angle away from vertical is 28 degrees at 30 minutes into the deployment. The tension at that time is negligible and should not present an alignment problem.

The next excursion is to 14 degrees at 100 minutes with still negligible tension values.

The highest excursion after significant tension build up (100 lbf) is to 10 degrees.

Once full deployment is reached a stable near zero angle condition is maintained.

Tether dynamics subsequent to normal release (end effector in place on tether) and for a broken tether are shown in the following charts A-6.2 thru A-6.5.

- SIMULATION RUNS OF DEPLOYMENT (USING TETHDY PROGRAM) INDICATE UNCOMPLICATED DEPLOYMENT PROCESS.
- INPLANE EXCURSION ANGLES:
  - 28 DEGREES AT 30 MINUTES (NEGLIGIBLE TENSION)
  - 14 DEGREES AT 100 MINUTES (NEGLIGIBLE TENSION)
  - LESS THAN 10 DEGREES AFTER TENSION BUILD UP TO 100 LBF.
- TETHER DYNAMICS SUBSEQUENT TO SHUTTLE RELEASE REQUIRE FURTHER ANALYSIS.

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Typical Orbit Paths

This and the following three views have been generated by a Martin Marietta orbital dynamics simulation computer model. The model is very versatile and capable of modeling a large range of forces that act on the orbiting system. However only gravitation, acceleration and tether tension forces have been modeled here since these are dominant; forces such as those produced by atmospheric drag and electrodynamic effects have not been included in the present analysis.

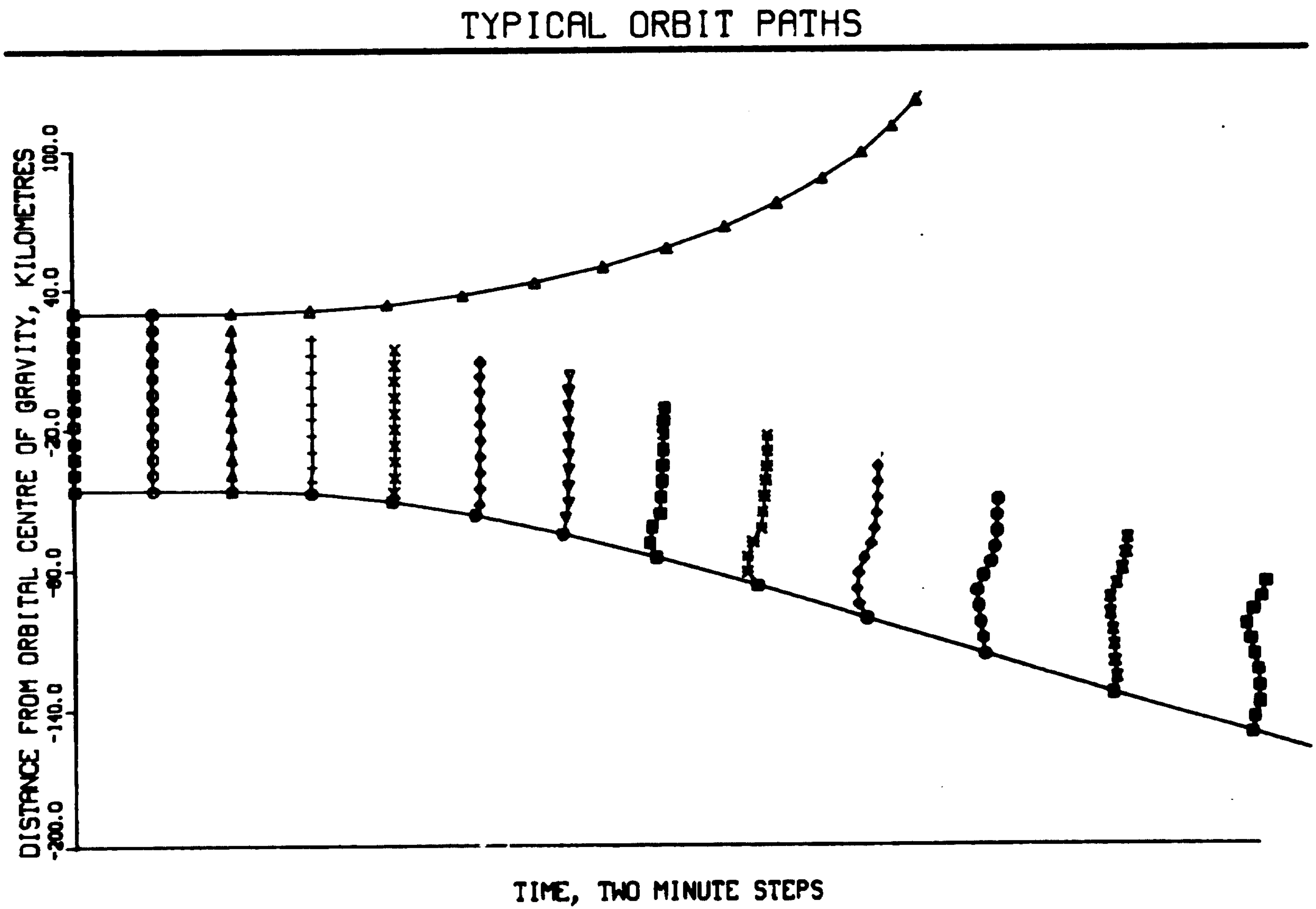
The tension forces have been modeled to correspond to a Kevlar 49 tether, which is relatively stiff, having a unit strain of about 0.003 at 15 kilonewtons. This point on the force/extension curve is appropriate for non-oscillating stationkeeping of the Space Station/Tether/Shuttle system under consideration. Use of a relatively stiff tether reduces the strain energy in the tether and hence the recoil after intentional separation or unintentional sever.

The system was initialized as lying on a radial from the center of the earth with no perturbation in orbital velocities, i.e., perfectly gravity-gradient stabilized.

The view of the typical orbit paths is that of an observer in a coordinate system originally rotating about the earth. This coordinate system has its origin at the initial orbital center of gravity of the tether system and has the center of the earth on its negative vertical axis. At the beginning of the simulation in effect the rotation of the coordinate system ceased so that orbital motion appears as translation along the horizontal axis.

The views of the Space Station and shuttle orbits thus appear as shown, the positions of the stations are shown by the symbols on the curved paths at simulated two minute intervals. The after-separation changes in orbital velocity and orbital altitude area are clearly apparent as deviations from equi-spacing and vertical translation on the graph. For presentation purposes there is severe horizontal scale compression compared with the vertical scale.

No compression exists within each individual image of the tether, however. Each image is to scale along both axes and hence the tether shape is visually correct at the instant of presentation. As is apparent these "snapshots" of the tether correspond to the symbol positions in the orbit paths.


TYPICAL ORBIT PATHS
DISTANCE FROM ORBITAL CENTRE OF GRAVITY, KILOMETRES
100.0
40.0
-20.0
-80.0
-140.0
-200.0
TIME, TWO MINUTE STEPS

Tether Configuration, Normal Release, With End Effector

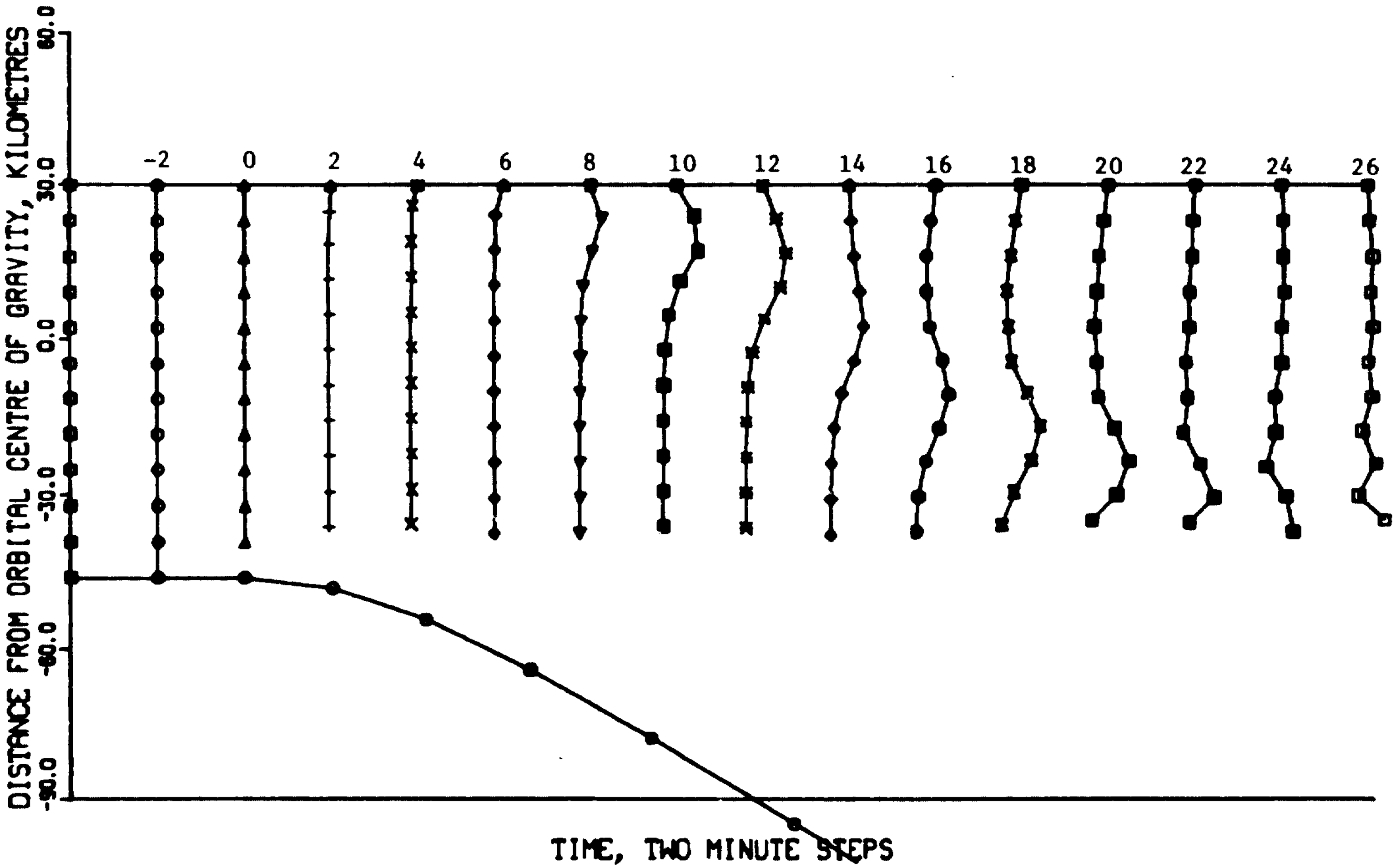
This view is similar to that of the orbit paths except that two more positional distortions have been made in the interest of clarity of presentation. Firstly the altitude change of the Space Station has been suppressed so that the images of the tether system are lined-up horizontally. Secondly the horizontal motions caused by Orbital effects also have been suppressed and the horizontal motion is solely a function of time. The benefit derived from these presentational modifications is a clear picture of the effect of separation/sever on the tether configuration.

The normal release mode is shown. Instantaneous release is assumed, i.e., no mechanism is considered that controls the rate at which the strain energy is applied to the orbiting system, this is considered to be the worst case for normal separation from the point of view of the reaction of the tether to the step in the tension at separation.

Separation occurs at the instant of the third tether image, time = 0. Separation is modeled at present by the total removal of the appropriate tether segment and explains the gap in the tether - the gap is not a large sudden decrease in the tether length. The bottom symbol still part of the tether after separation represents the end effector or mass 500 kg. After two minutes the tether has a net motion toward the Space Station due to the acceleration caused by the excess tension acting upward. The tether also is starting to fall behind the Space Station since each segment is now in a higher orbit than previously, this is true along its whole length. The tether is in tension along most of its length but is slack at the Space Station, this is shown by the spacing of the symbols along the tether. By +6 minutes the lack of tension at the Space Station allows the tether to fall toward the earth and around this time it is jerked at the Space Station as it again goes taut. This jerking has a significant component in the direction of the orbit and induces the wave clearly visible by +8 minutes. This wave travels down the tether and is attenuated on reflection.

It is to be expected that the reaction vibration in the tether would continue traveling up and down for many hours if undamped externally. In this normal separation mode the end effector is able to provide the necessary control for damping and subsequent reel-in and docking.

TETHER CONFIGURATION, NORMAL RELEASE, WITH END EFFECTOR



Tether Configuration, Sever Near Shuttle

This view is an examination of a potential hazard. The modeling is very similar to the previous case but without the 500 kg mass at the lower end. Hence this case models inadvertent sever of the tether, for example, by a meteorite.

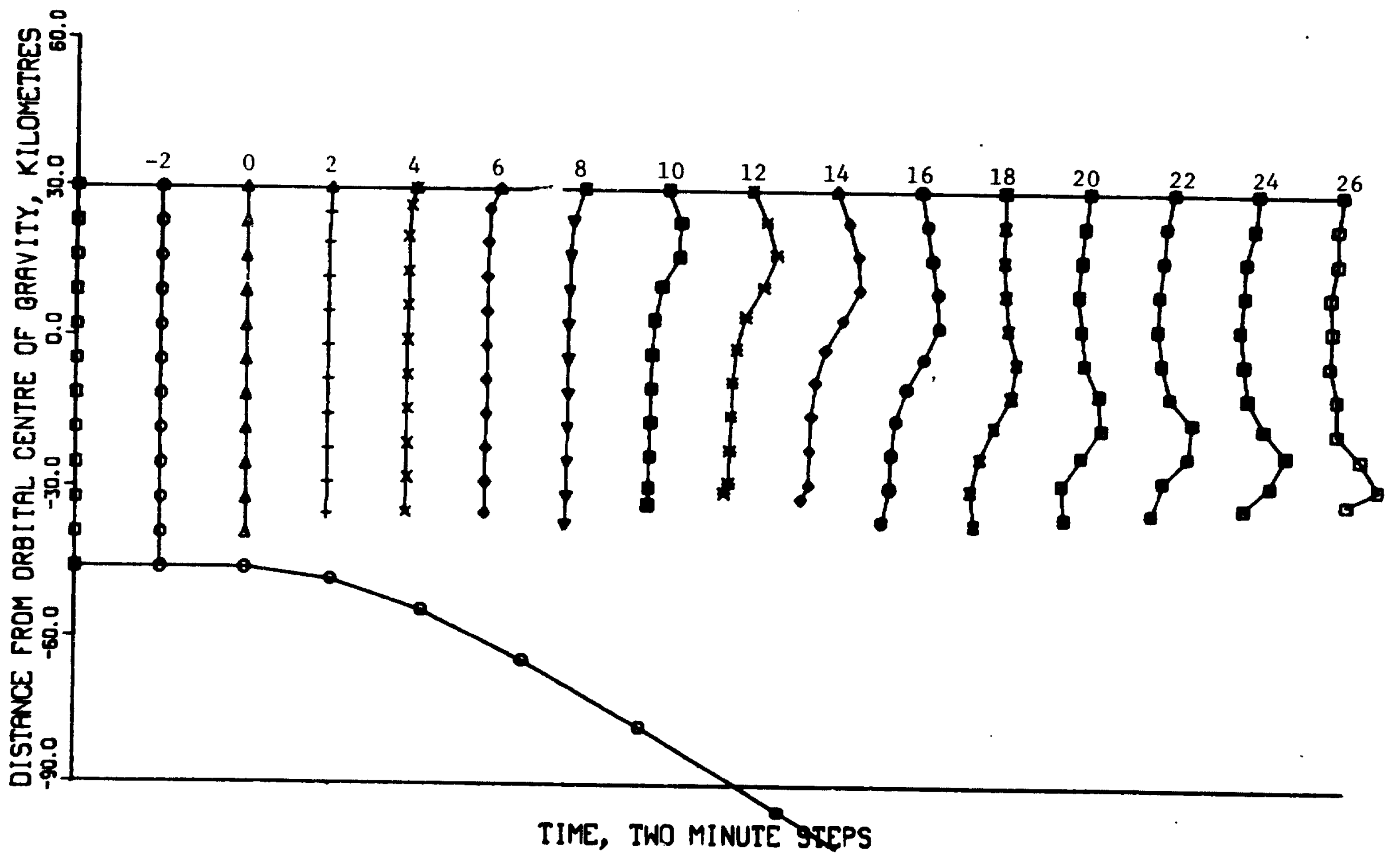
The reaction of the tether is similar to before, as might be expected. The differences are subtle; points to note are:

1) The wave is of longer wavelength and takes longer to travel the lengths of the tether, a result of the reduced effective tension.

2) The lack of a restraining gravity-induced load at the lower end of the tether allows bunching and possible self-entanglement at the lower end (time: 10 to 14 minutes).

An important point to be noted for this case is the apparent shortening of the uppermost length of tether-next to the station. This is indicative of a slack section in the tether. The model does not provide visibility of the actual shape of the tether in this interval of time and over this interval of tether length. Further more detailed simulation will be required to determine the shape in this region and the degree of entanglement risk to the station.

TETHER CONFIGURATION, SEVER NEAR SHUTTLE

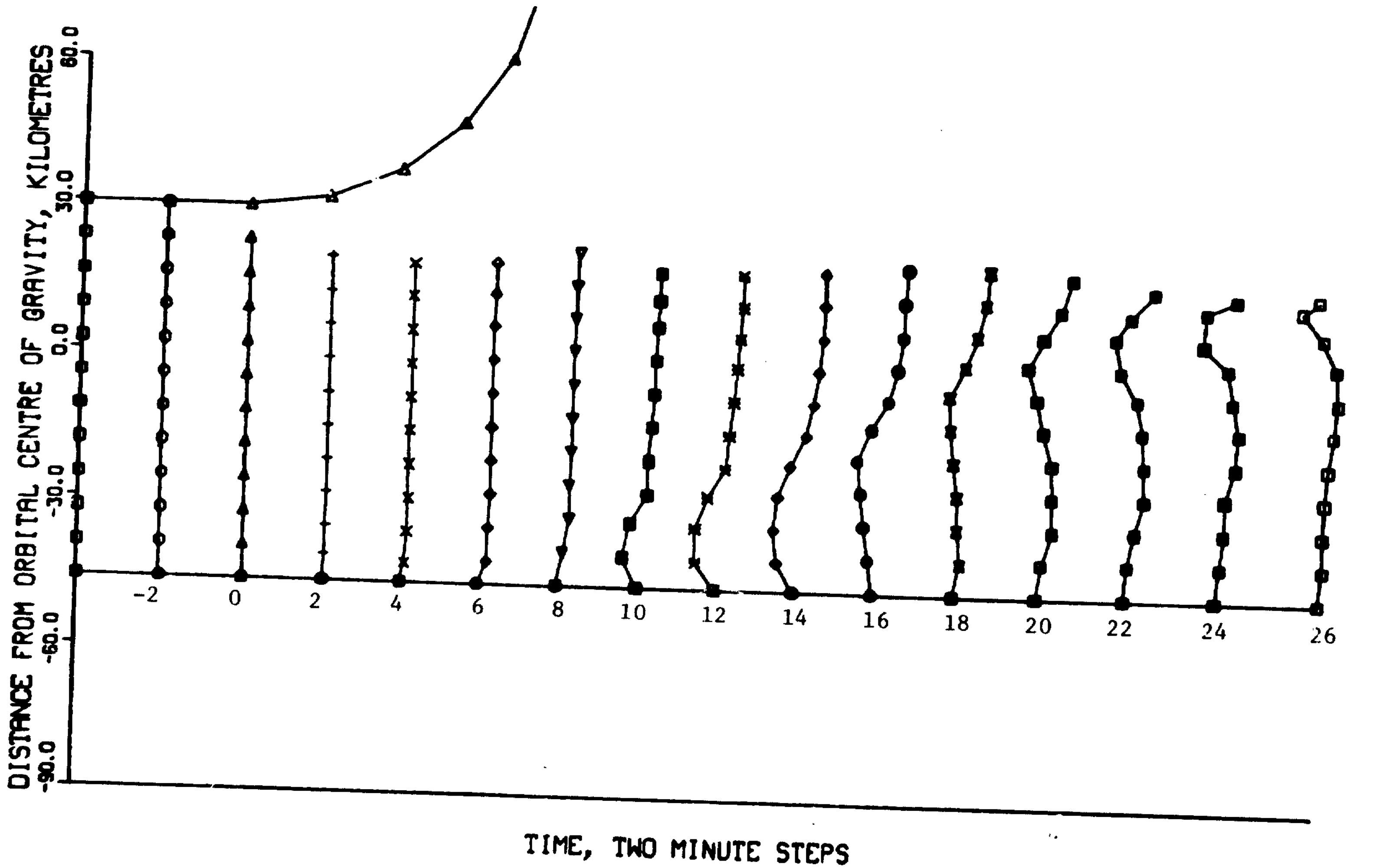


Tether Configuration, Sever Near Space Station

This view is also an examination of a potential hazard, it is the same case as shown in "typical orbit paths" on Chart A-6.2. The reversal of the effects on configuration is clearly seen, the tether first moves in front of its orbital position and then is jerked against the orbital motion.

This view shows that there is ample time for discarding a severed tether should a break occur remote from the Shuttle. It may be advantageous to wait until 12-14 minutes after separation when tether tension will tend to pull the tether end away from the Shuttle.

TETHER CONFIGURATION, SEVER NEAR SPACE STATION



Functional Requirements

Bridge Beam

- Provide a load path into the shuttle structure for the tether tension load (3300 lbf). The tension force is to be brought in on the center line of the Shuttle and located at a station which is close enough to the center-of-mass of the vehicle such that the hang angle can be adjusted to align the tension to the CM.

- Provide a single point release mechanism for the tether system end effector located at the center of the bridge beam (on the Shuttle center line).

- The Shuttle crew is to have control capability for the release mechanism. Requisite control interface with the Shuttle is required.

- The bridge beam is to be capable of retaining the tether end effector for reentry in event of an aborted tether release operation (e.g., broken tether).

End Effector

- Provide an attachment/release interface with the bridge beam mechanism.

- Incorporate a commandable thruster system to be used for retrieval operations of the tethered end effector. This could be either cold or hot gas.

- A cold gas system was selected for this concept to minimize contamination and plume impingement concerns.

- Provide a retro reflector to enhance tracking by the station radar.

- Provide Ku band transceiver and command decoder to provide control of the thruster system.

- Tether guillotine mechanism in event of an aborted deployment due to broken tether. This mechanism is to be controlled by the Shuttle crew and will require a control interface with the Shuttle.

- The estimated size and weight for the end effector are indicated. These values are not based on detailed analysis.

- The end effector must fit within the confines of the Shuttle cargo bay for contingency recovery.

ORBITER BRIDGE BEAM

- PROVIDES LOAD PATH INTO CARGO BAY SILL FITTINGS.
- PROVIDES ATTACH/RELEASE DEVICE FOR TETHER SYSTEM END EFFECTOR.
- END EFFECTOR ATTACH POINT ON SHUTTLE CENTERLINE.
- RELEASE OPERATION TO BE CONTROLLED BY ORBITER CREW.
- BRIDGE BEAM TO BE CAPABLE OF SUSTAINING RE-ENTRY/LANDING LOADS WITH END EFFECTOR IN PLACE AS A CONTINGENCY MODE.

END EFFECTOR

- ATTACHMENT PROBE FOR SINGLE POINT ATTACH/RELEASE DEVICE ON SHUTTLE BRIDGE BEAM.
- COLD GAS THRUSTER SYSTEM FOR END EFFECTOR RETRIEVAL OPERATIONS.
- RETROREFLECTOR FOR TRACKING BY SS RADAR SYSTEM.
- KU BAND TRANSCEIVER/COMMAND DECODER WITH HORN ANTENNA.
- TETHER GUILLOTINE MECHANISM (CONTROLLABLE BY SHUTTLE CREW).
- 1100 LBM (500 KG), 1M DIAMETER, 1M HIGH, (APPROXIMATE DIMENSIONS).
- DESIGN TO FIT WITHIN CARGO BAY ENVELOPE FOR CONTINGENCY RETURN.

(CONT'D)

Functional Requirements (Continued)

Tether

The functional requirements for the tether are indicated. Kevlar 49 was the specified material because of the high modulus.

Tether Tension Alignment Mechanism

- Provides a capability to align the tether tension force to the station center-of-mass to control torques on the station to an acceptable level. Detailed design and range of adjustment required is a function of the station design and are TBD at this time.
- The alignment device is to be automatically controlled by the station attitude control system. This will require a control interface.
- Berthing provisions for the system end effector are to be incorporated into the design of the alignment mechanism.
- A tether guillotine under the control of the station crew is required to sever the tether in event of a break or other circumstance where the tether cannot be retrieved.

TETHER

- PROTECTIVE JACKETED AGAINST RESIDUAL ATMOSPHERE IMPINGEMENT EFFECTS.
- TENSION LOAD 3300 LBF (14,700N).
- DESIGN FACTOR 2.5 OR BETTER.
- MATERIAL KEVLAR 49 BRAIDED CONSTRUCTION.
- SELECTED SIZE = 0.300 IN WITH 0.010 IN TEFLON BRAID JACKET FOR JACKETED DIAMETER OF 0.320 IN.
- MASS PER LENGTH 40 KG/KM.
- DEPLOYED LENGTH = 41 NMI (76 KM).
- DEPLOYED TETHER MASS = 3040 KG.
- MULTIPLE REUSE (20).

TETHER TENSION ALIGNMENT MECHANISM

- PROVIDES CAPABILITY TO ALIGN TENSION FORCE VECTOR WITH SS CM. (RANGE TBD).
- CONTROLLED BY SS ATTITUDE CONTROL SYSTEM.
- PROVIDES BERTHING FIXTURE FOR TETHER END EFFECTOR.
- PROVIDES TETHER GUILLOTINE MECHANISM.

(CONT'D)

Functional Requirements (Continued)

Tether Reel

- Provision to hold 43 nmi (80 km) of the specified tether.

- Capable of developing adequate braking torque to halt the deployment at any stage.

- Braking torque is to be developed by use of the reel drive motor used in a generator mode such that the developed energy is primarily in the form of electrical power.

- The reel drive shall be adequately sized to perform the deployment to full tether length in one 8 hour crew shift.

- The average power developed over the 8 hour period of deployment is 19.5 kW. The peak power will depend on the detail design of the reel and drive and the deployment control laws. A preliminary estimate is for a peak power of 50 kW (67 hp). Note that this is the total power developed and includes the portion dissipated in generator heating.

High Temperature Radiator

- Where any beneficial utilization of the power generated by the deployment can be made it will reduce the requirement for rejecting this energy as heat. In general, for this study it has been assumed that such a utilization will not be possible and the energy must be rejected. To accomplish this a high temperature resistive load bank and reflective radiator will be used to radiate the energy as waste heat.

TETHER REEL

- REEL CAPACITY FOR 43 NMI (80 KM) OF TETHER.
- BRAKING TORQUE CAPABILITY TO HALT DEPLOYMENT AT ANY POINT.
- BRAKING BY GENERATOR MODE OF REEL DRIVE MOTOR.
- ADEQUATE POWER CAPABILITY TO PERFORM DEPLOYMENT IN 8 HOURS OR LESS.
- AVERAGE POWER DEVELOPED OVER 8 HOUR DEPLOYMENT IS 26 HP (19.5 KW).
- PEAK POWER IS 67 HP (500 KW).

HIGH TEMPERATURE RADIATOR

- CAPABLE OF RADIATING ENERGY GENERATED DURING SHUTTLE TETHER DEPLOYMENT.

Space Station/Shuttle Docked

The concept incorporates the center-of-mass (CM) alignment boom with reel system around the standard docking port. This approach provides an efficient arrangement for activities performed relating to initial installation of the system, personnel operations in a localized area for shuttle payload transfer operations and accessibility to the deorbit equipment.

The CM alignment boom rotates 360° around the station centerline for total radial coverage. The traveling carriage provides axial movement which results in total coverage over the area within a 70 foot diameter circle. The purpose of this mechanism is to direct the tether tension vector thru the station center of mass during shuttle deorbit. This will accommodate station CM offsets and shuttle swing during deployment.

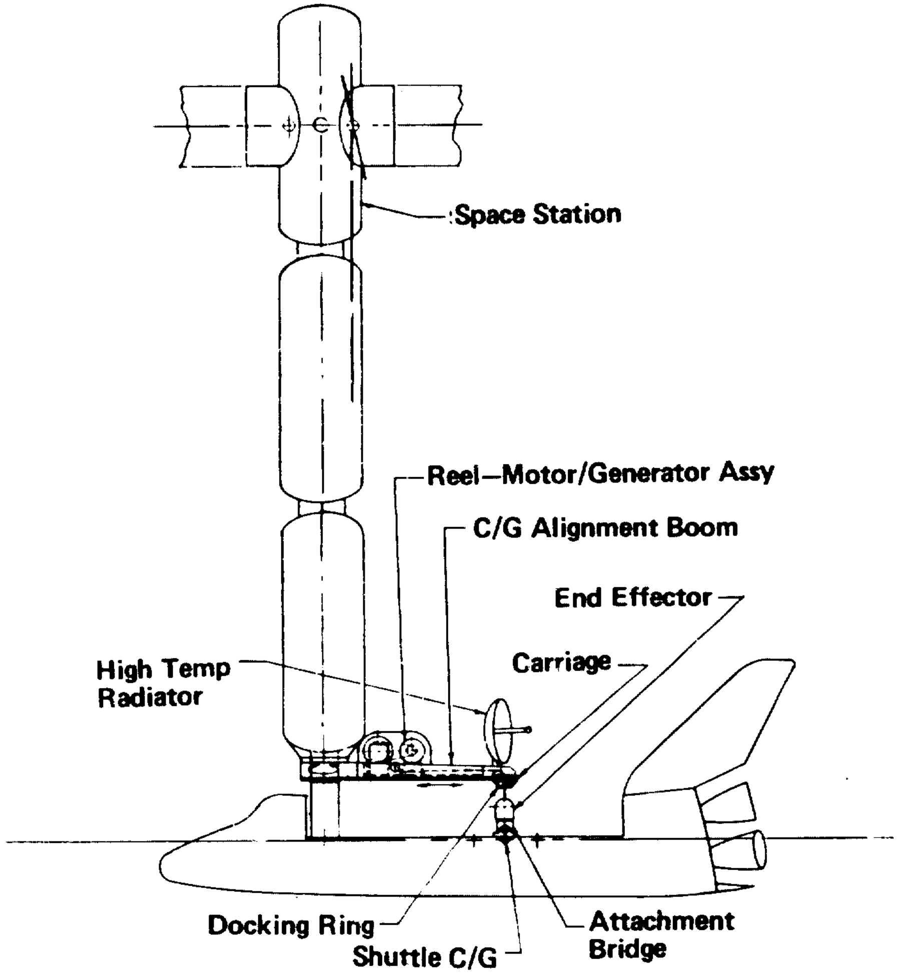
Mounted on the boom is the tether storage reel and motor/generator assembly. The tether exits thru the carriage and attaches to the end effector. Also shown is a high temperature radiator to reject the waste energy generated during the shuttle deployment.

The end effector attaches to the shuttle attachment bridge beam where shuttle release at final deployment is initiated. The bridge beam will be secured at sill trunnion fittings near the shuttle CM.

After shuttle release, the end effector is retrieved and docked in the docking ring and positioned for subsequent shuttle deorbit operations. The bridge beam remains with the shuttle.

The estimated mass for the station mounted hardware is 12,700 lbm (5770 kg). This includes the mass of the tether which is 7,000 lbm (3180 kg).

Space Station/Shuttle Docked



Shuttle Deployment From Space Station

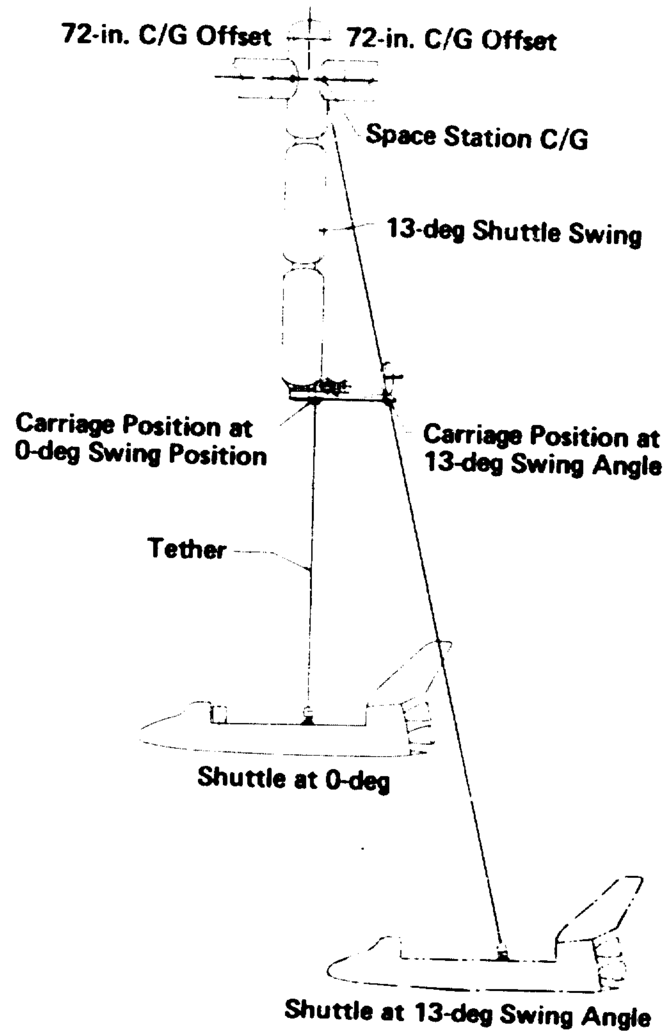
This picture describes the function of the CM alignment boom during a typical shuttle deorbit operation.

A 72 inch space station CM offset is assumed. If the shuttle is suspended at a zero tether angle, the carriage will have traveled to a position in line with the shuttle and space station centers of mass.

When the shuttle swings in or out of plane of the space station geometry, the boom will rotate to the resultant combined angle. The carriage will travel radially to position itself in line with the combined shuttle and space station center of mass.

This system will be continually active throughout the deployment phase and will receive drive control information from the space station attitude determination system. This allows the space station to maintain a stable undisturbed attitude during shuttle deorbit.

Shuttle Deorbit from Space Station



Bridge Beam-Shuttle Installation

The Shuttle deorbit mission requires tether attachment to Shuttle be made at the standard shuttle primary load carrying fittings. (Sill trunnion and keel fittings).

This is accomplished with the bridge beam shown here. This bridge beam must be brought up by the shuttle for each intended usage.

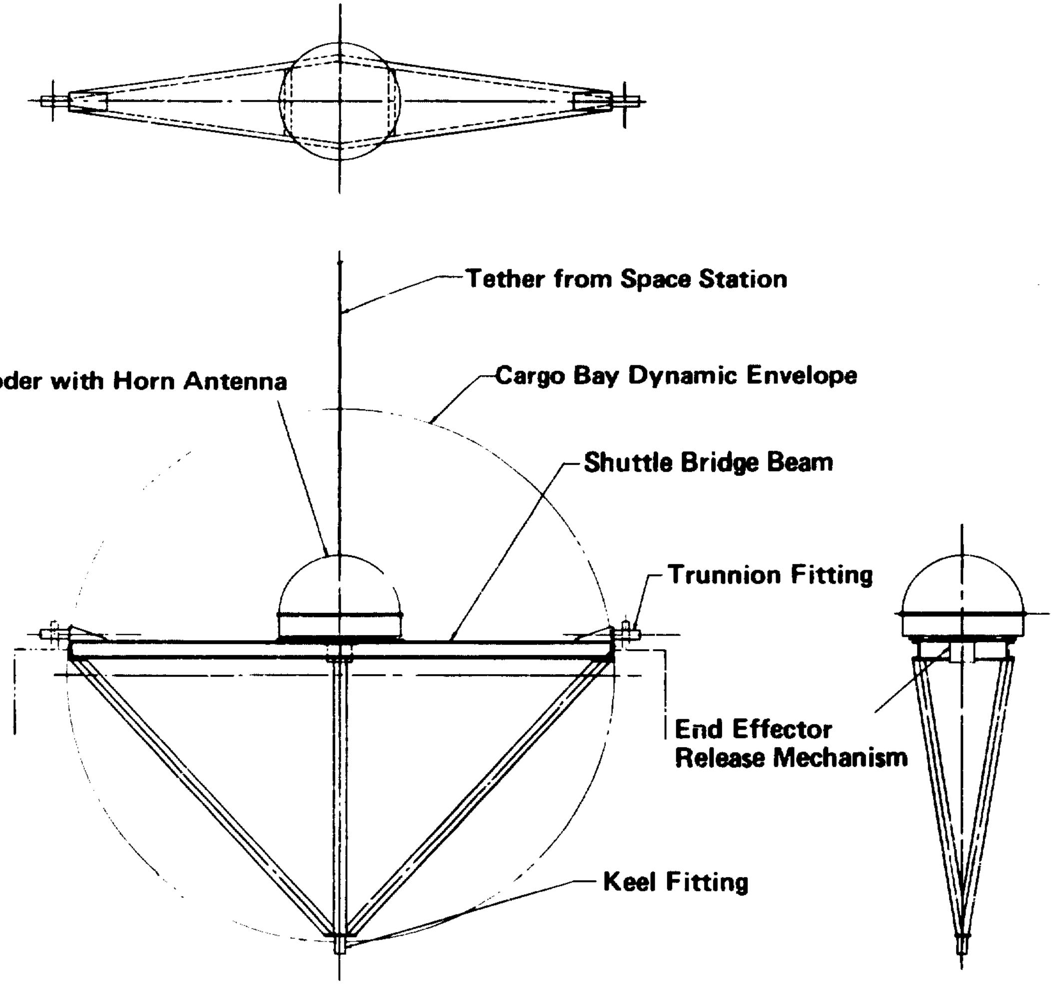
The end effector is the interface module which is latched to the bridge beam while Shuttle is docked to the Space Station. The mated system is deployed to the reentry altitude under control of the reel deployment mechanism. At this point, the end effector release mechanism is activated by the Shuttle crew, releasing Shuttle for final reentry.

The end effector is then retrieved and stowed at the Space Station for future use.

The end effector contains all support systems necessary for tracking, communications and propulsion. These systems are primarily used during end effector retrieval. A tether cutter (guillotine) is provided in the event of release mechanism failure. In this case the end effector will return to Earth with the Shuttle.

Estimated mass of the bridge beam plus the required Shuttle trunnion fittings is 300 lbm (136 kg). The mass of the end effector shown is not included.

Bridge Beam-Shuttle Installation



Bridge Beam - Shuttle Installation

Safety Considerations

Tether recoil after a break during deployment could result in broken tether ends impacting onto both shuttle cargo bay and the space station. Further analysis of tether recoil dynamics is needed to confirm the problem.

Aborted tether deployment operation raises an issue of requirement to retain adequate OMS fuel on-board the shuttle to complete de-orbit operation from any intermediate altitude, this requirement negates potential propellant savings from a tether effected orbiter re-entry.

- BROKEN TETHER RECOIL IMPACT.
- CONTINGENCY DEBOOST OMS PROPELLANT REQUIREMENTS.

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Areas Needing Further Study

Tether recoil dynamics both after a planned release and after a break in the tether need further analysis. Better data on recoil characterization of candidate tether construction in needed as well as improved and verified simulation programs.

The potential beneficial uses of the Space Station for the power generated during deployment need to be explored. This is energy in the form of electrical power.

The consequences to Space Station operations of an orbit boost to the altitudes described needs to be investigated. Some of the identified areas of concern are.

- Performance penalties for subsequent Shuttle missions to the station because of the increased altitude for rendezvous.
- The impact on coordinated operations with free flying platforms which make up a part of the station architecture concept.
- Increased radiation dose to the crew at the higher altitude.

The potential for using the angular momentum added to Space Station to, in turn, carry out tether assisted launches to geosynchronous orbit.

The deorbit concept explored for this study results in large and somewhat indigestable increments of angular momentum and energy into the station orbit. We need to explore less ambitious deployments and assess their benefits.

One of the ground rules adopted for this study is a requirement to carry sufficient OMS propellant on board the Shuttle to carryout a reentry from any stage of deployment (in case of abort). This rule should be re-examined to determine if it is overly stringent.

The effects of the induced acceleration levels on the station subsystems need to be studied.

Possible impingement effects of Shuttle RCS plumes on the tether need to be determined.

Possible interference between the bridge beam and some of the most typical return payloads should be studied for potential conflicts.

- TETHER RECOIL DYNAMICS
  - AFTER PLANNED SHUTTLE SEPARATION
  - AFTER TETHER BREAK.
- IDENTIFY POTENTIAL USES ON SS FOR ELECTRICAL POWER GENERATED DURING DEPLOYMENT.
- CONSEQUENCES OF BOOSTING SS ALTITUDE TO UPPER EDGE OF SHUTTLE ACCESSIBILITY RANGE
  - SUBSEQUENT MISSION PAYLOAD PENALTIES
  - IMPACT ON FREE FLYING PLATFORM OPERATIONS
  - RADIATION DOSAGE.
- DEFINE TETHER AIDED LAUNCH TECHNIQUES FOR GEOSYNC MISSIONS.
- CONSIDER POTENTIAL BENEFITS FROM LESS AMBITIOUS SHUTTLE DEORBIT OPERATIONS AT MORE FREQUENT INTERVALS
  - LESS MASSIVE HARDWARE
  - MORE DIGESTABLE INCREMENTS OF ANGULAR MOMENTUM.
- DETERMINE POSSIBILITY OF OFF-LOADING OMS PROPELLANT NOT REQUIRED - SAFETY ISSUE.
- DETERMINE EFFECT (IF ANY) OF INDUCED ACCELERATION LEVELS (DURING SHUTTLE DEPLOYMENT) ON SS STRUCTURES AND OPERATIONS (E.G., SOLAR ARRAYS, MATERIALS PROCESS EXPERIMENTS).
- DETERMINE EFFECTS OF SHUTTLE RCS PLUME IMPINGEMENT ON TETHER.
- DETERMINE POTENTIAL INTERFERENCE BETWEEN TYPICAL SHUTTLE RETURN PAYLOADS (E.G., LOGISTICS MODULE) AND THE TETHER SYSTEM BRIDGE BEAM.

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Technology Development Needs

- Efficient and compact radiators will be required to reject the substantial amounts of energy generated during the deployment operation.
- Tether construction methods with inherently damped recoil characteristics are the most desirable solution to the tether recoil after release. As an alternative, methods of damping the recoil by design of the release mechanisms and/or process is needed.
- Design of tension alignment mechanisms for the required level of tension force and for the range of variation of the station center-of-mass is needed.
- The re-use of tethers is an important aspect of the concept. The construction of tethers to resist the tension level excursions and to be resistant to the degradation effects of residual atmosphere impingement is a needed development.

STS Technology Development Missions

- An anologus deployment to this concept would involve the deorbit deployment of an ET from the Shuttle.
- Initial demonstration would not require the retrieval of the tether.
- Tether retrieval operations could be verified on follow-on versions.
- The ability to deorbit ET from Shuttle by tether is of interest for its own sake.
  - Scavenging of residual cryogen fuels from the ET
  - Enhanced choice of ET re-entry impact locations

TECHNOLOGY DEVELOPMENT NEEDS

- METHODS OF UTILIZING OR EFFICIENTLY REJECTING AS WASTE HEAT THE ELECTRICAL POWER DEVELOPED DURING SHUTTLE DEPLOYMENT.
- ALTERNATIVE METHODS OF DAMPING TETHER RECOIL DYNAMICS
  - TETHER CONSTRUCTION FOR INTERNAL DAMPING
  - DAMPED RELEASE TECHNIQUES.
- TETHER TENSION ALIGNMENT MECHANISMS FOR SS INSTALLATION.
- TETHER CONSTRUCTION TO ENHANCE REUSE CAPABILITY.

POTENTIAL STS TECHNOLOGY DEVELOPMENT MISSIONS

- DEMONSTRATE TETHER DEPLOYMENT OF MASSIVE BODIES BY A DEORBIT OF AN EXTERNAL TANK FROM THE SHUTTLE.
- INITIAL DEMONSTRATION WOULD JETTISON TETHER WITH ET.
- SUBSEQUENT DEMONSTRATIONS COULD EFFECT TETHER RECOVERY.
- CAPABILITY TO DEORBIT ET HAS ITS OWN INHERENT OPERATIONAL BENEFITS.

Shuttle Conventional Deorbit From Space Station

As currently envisioned, the Orbiter will undock from the docking port at the Space Station as it approaches the time and particular earth orbit pass that will allow the Orbiter to land at the ELS (Eastern Launch Site).

The Orbiter will then proceed to move a sufficient distance from the Space Station, using RCS translation, to allow the OMS engines to safely fire. Prior to this time the cargo bay doors would be closed and final checks made.

At the appropriate time the OMS engines will be fired for the retro maneuver to place the Orbiter at the desired reentry point. (Estimated OMS propellant usage is 6000-8000 lb (2720-3630 kg).

SHUTTLE CONVENTIONAL DEORBIT FROM SPACE STATION

- SHUTTLE UNDOCKS FROM DOCKING PORT.
- ORBITER MOVES AWAY FROM SPACE STATION FOR DEORBIT SEQUENCE.
- DEORBIT SEQUENCE INITIATED FROM APPROXIMATELY 270 NMI (500 KM) ALTITUDE.
- ESTIMATED PROPELLANT REQUIRED FOR DEORBIT 6000-8000 LB (2720-3630 KG).

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1. A POTENTIAL EXISTS FOR SAVING SEVERAL THOUSANDS OF POUNDS OF OMS PROPELLANT WITH A TETHERED SHUTTLE DEORBIT. PROPELLANT SAVINGS REALIZED COULD BE TRANSLATED INTO INCREASED CARGO WEIGHT DELIVERED TO THE SPACE STATION.

2. OFF-LOADING OMS PROPELLANT WOULD CAUSE A RISK SITUATION IN THE EVENT OF TETHER FAILURE, REQUIRING THE ORBITER TO RETURN TO THE SPACE STATION. PROVIDING FOR AN ACCEPTABLE RISK WOULD NEGATE ANY APPARENT PROPELLANT SAVINGS OR CARGO WEIGHT INCREASE.

3. LARGE AMOUNTS OF ELECTRICAL POWER ARE GENERATED IN THE RELATIVELY SHORT TIME OF TETHER DEPLOYMENT AND MUST BE RAPIDLY UTILIZED OR DISSIPATED.

4. THE TETHERED SHUTTLE DEORBIT HAS A LARGE IMPACT ON THE SPACE STATION ORBIT. MAXIMUM ALTITUDE IS INCREASED FROM 270 NMI (500 KM) TO 383 NMI (79 KM). ORBIT DRAG DECAY TIME BACK TO THE ORIGINAL ORBIT COULD TAKE FROM 1 1/2 YR TO 7 YR.

5. THE INCREASED ANGULAR MOMENTUM OF THE SPACE STATION ORBIT HAS TWO PRIMARY APPLICATIONS:

   A) TO REDUCE STATIONKEEPING PROPELLANT REQUIREMENTS (ESTIMATED AT 1500-3000 LB (680-1361 KG) PER 90 DAYS).

   B) TO REDUCE OMV, OTV, OR OTHER STAGE PROPELLANT REQUIREMENTS BY USING TETHERED LAUNCHES. ("MOMENTUM BANK ACCOUNT" CONCEPT).

6. PAYLOAD CAPABILITY OF SUBSEQUENT SHUTTLE FLIGHTS IS SUBSTANTIALLY PENALIZED TO ACCOMPLISH DIRECT INSERTION AT THE HIGHER SPACE STATION ALTITUDE.

1. A TETHERED SHUTTLE DEORBIT FROM THE SPACE STATION THAT WOULD PRODUCE SHUTTLE PERIGEE ALTITUDES BELOW 100 NMI (185 KM) IS NOT RECOMMENDED.
2. INVESTIGATE A SMALLER MOMENTUM TRANSFER AT SHUTTLE DEPARTURE FOR ORBIT STATIONKEEPING BENEFIT.
3. INVESTIGATE UTILIZATION OF A DEDICATED HEAVY PLATFORM TO SERVE AS AN ANGULAR MOMENTUM ACCUMULATOR FOR SHUTTLE DEORBIT AND TETHER ASSISTED LAUNCHES.

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SECTION B

TETHER EFFECTED ORBIT BOOST OF A SPACECRAFT (AXAF) INTO ITS OPERATIONAL ORBIT FROM THE SHUTTLE.

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Concept Definition

AXAF was selected as a good candidate for tethered insertion (from the Shuttle) into its final operational circular orbit of 320 nmi (593 km) since it is close to the altitude limit for direct insertion for Orbiter payloads of this magnitude and can also be accommodated with reasonable tether lengths.

Angular momentum will be transferred from the Orbiter in an elliptical orbit to the AXAF spacecraft, causing the AXAF to be boosted into a higher energy orbit and causing the Orbiter to move to a lower orbit.

The basic objectives of this approach are to place the AXAF spacecraft into its final operational orbit without the use of integral propulsion or direct insertion by the Shuttle and to reduce Orbiter OMS propellant requirements for both AXAF deployment and subsequent deorbit operations.

CONCEPT DEFINITION

- o USE A TETHER TO BOOST THE AXAF (ADVANCED X-RAY ASTROPHYSICS FACILITY) SPACECRAFT INTO ITS OPERATIONAL ORBIT BY THE SHUTTLE.
- o ANGULAR MOMENTUM WILL BE TRANSFERRED FROM THE SHUTTLE TO AXAF CAUSING THE ORBITER TO MOVE TO A LOWER ORBIT.

OBJECTIVES

- o PLACE THE AXAF SPACECRAFT INTO ITS FINAL OPERATIONAL ORBIT WITHOUT THE USE OF INTEGRAL PROPULSION OR DIRECT INSERTION BY SHUTTLE.
- o REDUCE ORBITER OMS PROPELLANT REQUIREMENTS FOR BOTH AXAF DEPLOYMENT AND ORBITER DEORBIT OPERATIONS.

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Ground Rules and Assumptions

The tether length and Shuttle eccentric orbit shall be selected to place the AXAF spacecraft into its circular operational orbit at 320 nmi (593 km) while assuring that the Orbiter does not drop below 100 nmi (185 km) altitude after tether release. A dedicated Shuttle mission is assumed.

All calculations are based on an Orbiter mass of 205 klb (93,000 kg) after AXAF deployment. The AXAF satellite is assumed to have a mass of 20 klb (9,070 kg).

The maximum time for deploying the tether and stabilizing the spacecraft is one 8 hr. shift. An additional 8 hr shift period is scheduled for ground crew monitoring and AXAF initialization before release. Deployment and stationkeeping of the AXAF above the Orbiter will be accomplished in a manner to minimize tether deviations in angle or angular rate from the zenith direction. The maximum time for retrieving the tether and end effector is also one 8 hr. shift.

- SELECT TETHER SEPARATION DISTANCE AND SHUTTLE ECCENTRIC ORBIT PARAMETERS TO PLACE THE AXAF INTO A 320 NMI CIRCULAR ORBIT WHILE ASSURING THAT THE ORBITER PERIGEE DOES NOT FALL BELOW 100 NMI (185 KM) AFTER TETHER RELEASE. A DEDICATED STS MISSION IS ASSUMED.

PRIMARY MASSES

- ORBITER MINUS AXAF MASS 205 KLB (93,000 KG). THIS ABOVE INCLUDES 15 KLB (6,800 KG) FOR AXAF ASE, TSS, END EFFECTOR, RMS, AND TBD.
- AXAF SATELLITE MASS 20 KLB (9,070 KG).

DEPLOYMENT/RETRIEVAL

- DEPLOY TETHER UPWARD WITHIN ONE 8 HR. SHIFT.
- ALLOW AN ADDITIONAL 8 HR SHIFT FOR AXAF INITIALIZATION BY GROUND CONTROL BEFORE RELEASE.
- DURING STATIONKEEPING PHASES, PRECEDING RELEASE, STABILIZE THE TETHER IN THE ZENITH DIRECTION (I.E., ZERO LIBRATION ANGLE AND RATE IN ALL DIRECTIONS).
- RETRIEVE TETHER AND END EFFECTOR WITHIN ONE 8 HR. SHIFT.

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Operations Concept

Using the RMS, erect AXAF in the cargo bay on the TSS end effector and latch in place. The RMS is then re-stowed. Tether deployment of AXAF is initiated in the zenith direction by firing the end effector thrusters and releasing the tie down-latches. After adequate separation of the AXAF has occurred, the TSS boom and guy cable are deployed.

AXAF separation is continued upward with the end effector thrusters until approximately 1 km. After this point further deployment of AXAF is controlled by the tether system operator using gravity gradient forces. The Shuttle orientation is adjusted as required to cause the tether tension force to pass through the Orbiter CM.

At the specified tether length deployment will stop and stationkeeping will begin. AXAF stationkeeping will be continued during a period of satellite checkout by the AXAF ground crew. After checks are completed the Orbiter crew will release the AXAF from the end effector at the appropriate time.

After tether release, the tether system operator will retrieve the tether, capture and stow the end effector and boom and secure the tether system.

1. USING RMS, ERECT AXAF IN CARGO BAY ON TSS END EFFECTOR AND LATCH IN PLACE. RMS IS RE-STOWED.
2. INITIATE TETHER DEPLOYMENT OF AXAF ABOVE ORBITER BY FIRING END EFFECTOR THRUSTERS AND RELEASING TIE-DOWN LATCHES. THE BOOM AND GUY CABLES ARE DEPLOYED AFTER AXAF HAS MOVED A SAFE DISTANCE AWAY FROM THE SHUTTLE.
3. CONTINUE AXAF SEPARATION WITH END EFFECTOR THRUSTER ALONG ZENITH DIRECTION TO APPROXIMATELY 1 KM. ADJUST SHUTTLE ORIENTATION SUCH THAT TETHER TENSION FORCE CONTINUES TO PASS THROUGH THE SHUTTLE CM.
4. AFTER THIS POINT FURTHER DEPLOYMENT OF THE AXAF IS CONTROLLED BY THE TETHER SYSTEM OPERATOR USING GRAVITY GRADIENT FORCES.
5. AT SPECIFIED DEPLOYMENT LENGTH STOP DEPLOYING AND STABILIZE.
6. AXAF STATIONKEEPING WILL BE CONTINUED DURING A PERIOD OF SATELLITE CHECKOUT BY THE GROUND CREW.
7. ORBITER CREW INITIATES RELEASE AT SPECIFIED TIME.
8. TETHER SYSTEM OPERATOR INITIATES TETHER RETRIEVAL.
9. CAPTURE AND STOW END EFFECTOR.
10. RETRACT AND STOW BOOM.
11. SECURE TETHER SYSTEM.

AXAF Deployment Sequence/Shuttle Response

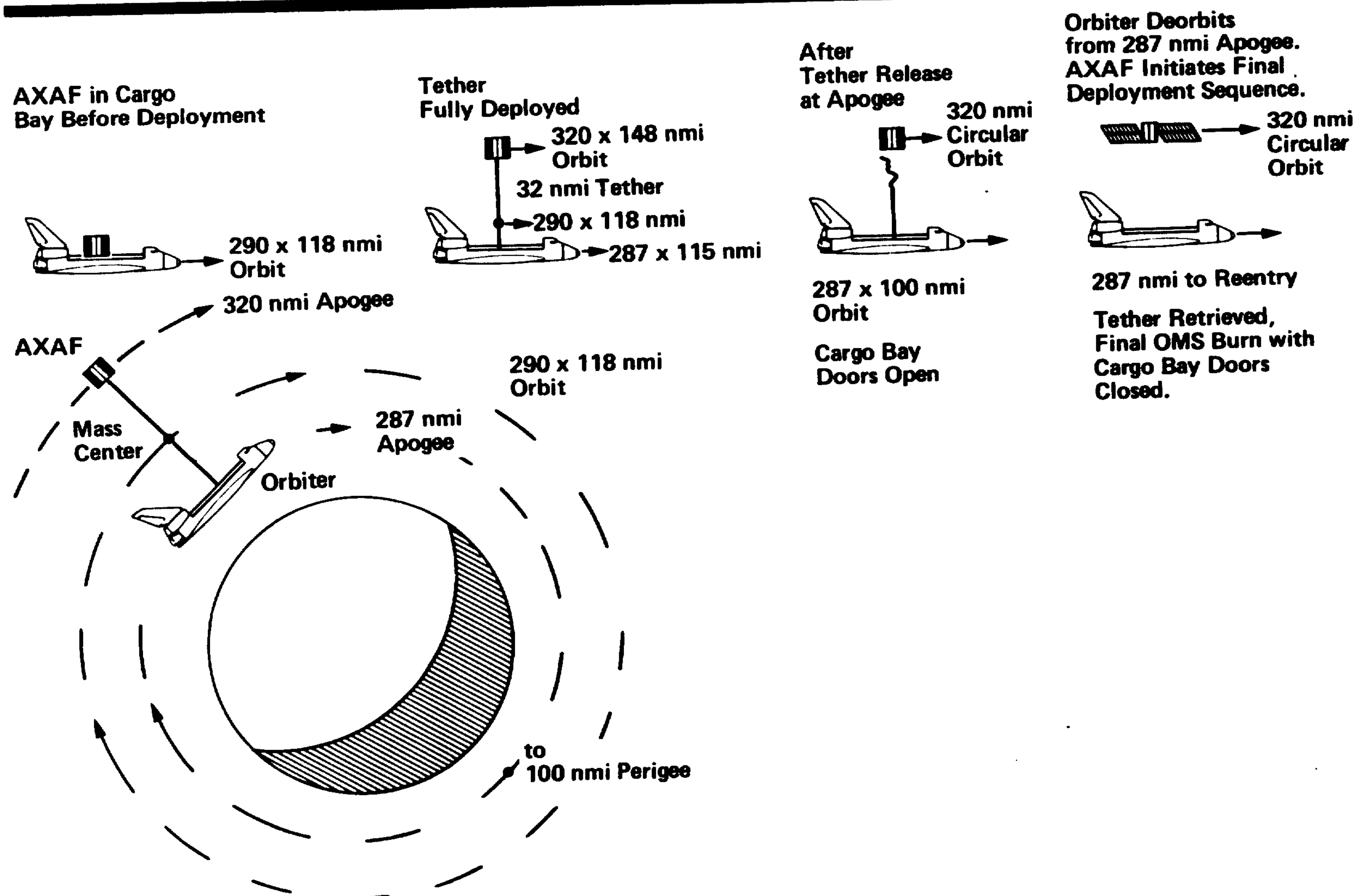
The Orbiter with its dedicated AXAF payload is initially injected into an eccentric orbit with a perigee of 118 nmi (219 km) and an apogee of 290 nmi (537 km) at an orbit inclination of 28.5 degrees. The eccentric orbit is necessary to allow a direct tether insertion (no additional propulsion to the payload) into the final AXAF circular operational orbit.

A tether length of approximately 33 nmi (61 km) is selected to insure that the Orbiter altitude does not fall below 100 nmi (185 km) after the AXAF is released into its final orbit.

As momentum is exchanged between the AXAF spacecraft and the Orbiter during tether deployment, the combined center of mass remains in the original 118 nmi (219 km) by 290 nmi (537 km) orbit. The AXAF ascends to a 320 nmi (593 km) apogee by 148 nmi (274 km) perigee and the Orbiter descends to a 287 nmi (531 km) apogee by 115 nmi (213 km) perigee at the end of tether deployment.

When the AXAF is separated from the end effector (tether release) at apogee, the AXAF is inserted directly into a 320 nmi (593 km) circular orbit. Simultaneously, the Orbiter will be at the apogee of a 287 nmi (531 km) by 100 nmi (185 km) eccentric orbit, from which the Orbiter will make a final OMS burn at a later apogee passage for reentry. Prior to this time the tether and end effector will be retrieved and stowed, and the cargo bay doors will be secured.

AXAF Deployment Sequence/Shuttle Response



Orbit Overview

Tether System Design Considerations/Orbiter Considerations

The AXAF spacecraft is placed on the TSS end effector by the RMS and latched in place in the cargo bay. The RMS is then re-stowed. Deployment is initiated by activating the end effector thrusters and releasing the tie-down latches.

Torques on the Orbiter caused by tether operations will be maintained near zero by controlling Orbiter orientation to align the tether tension vector with CM. Braking energy generated by AXAF tethered deployment will be dispositioned on the Orbiter.

Normal tether release at AXAF end effector interface will be performed by the Orbiter crew with ground crew backup capability. Emergency tether release (in case of tether failure, etc.) will be by guillotine controlled by the Orbiter crew.

The Orbiter will track the end effector during deployment and retrieval with its tracking and ranging system (Radar) and also maintain a command/data link with the end effector.

ORBITER CONSIDERATIONS

- AXAF IS PLACED ON TSS END EFFECTOR BY RMS AND LATCHED IN PLACE. RMS IS RE-STOWED. DEPLOYMENT IS INITIATED BY FIRING END EFFECTOR THRUSTERS AND RELEASING TIE-DOWN LATCHES.
- TORQUE INTO THE ORBITER IS CONTROLLED BY ORBITER ORIENTATION TO ALIGN TETHER TENSION WITH THE CM.
- BRAKING ENERGY GENERATED DURING TETHER DEPLOYMENT WILL BE DISPOSITIONED ON THE ORBITER.
- NORMAL TETHER RELEASE WILL BE PERFORMED BY THE ORBITER CREW WITH GROUND BACKUP CAPABILITY.
- EMERGENCY TETHER RELEASE (IN CASE OF BREAK, ETC.) WILL BE BY GUILLOTINE CONTROLLED BY THE ORBITER CREW.
- THE ORBITER TRACKS THE END EFFECTOR DURING DEPLOYMENT AND RETRIEVAL WITH ITS TRACKING AND RANGING SYSTEM (RADAR).
- A COMMAND/DATA LINK WILL BE MAINTAINED BETWEEN THE ORBITER AND END EFFECTOR.

Tether System Design Considerations (Continued)

The required end effector shall be a device with a propulsion/attitude control system (cold gas) to provide 6 degree of freedom control during tether deployment and retrieval.

The AXAF characteristics used for this analysis include the mass of 20 klb (9,070 kg), and overall length of 43 ft (13.1 m), and a diameter of 14 ft (4.3 m).

The AXAF with end effector and tether attached is initially deployed by the end effector. As gravity gradient forces build up they provide the major separation force with the end effector assisting and providing active control of libration angles and rates until full tether length is reached.

After an 8 hr (maximum) tether deployment and stationkeeping period, the AXAF ground crew will monitor the system for an additional 8 hrs until the time for release into the 320 nmi circular orbit).

END EFFECTOR REQUIREMENT

- o AN END EFFECTOR DEVICE WITH A PROPULSION (COLD GAS)/ATTITUDE CONTROL SYSTEM FOR 6 DEGREE OF FREEDOM CONTROL DURING TETHER DEPLOYMENT AND RETRIEVAL IS REQUIRED.

AXAF SATELLITE CONSIDERATIONS

- o MASS 20 KLB (9,070 KG)
- o LENGTH 43 FT (13.1 M)
- o DIAMETER 14 FT (4.3 M)
- o AXAF WITH END EFFECTOR AND TETHER ATTACHED IS DEPLOYED BY THE END EFFECTOR.
- o END EFFECTOR/GRAVITY GRADIENT FORCES PROVIDE FOR POSITIVE SEPARATION UNTIL FULL TETHER LENGTH IS REACHED.
- o DEPLOYMENT AND STABILIZATION ARE TO BE PERFORMED IN AN 8 HR CREW SHIFT.
- o AXAF GROUND CREW WILL INITIALIZE THE SPACECRAFT AND PERFORM LAUNCH READINESS CHECKOUT FOR AN 8 HOUR PERIOD.

Tether System Design Considerations (continued)

Design considerations for the tether and reel are given.

TETHER SYSTEM DESIGN CONSIDERATIONS (CONTINUED)

TETHER

- o RETRIEVAL OF TETHER AND END EFFECTOR REQUIRED
- o NO REUSE OF TETHER - NO JACKET REQUIRED
- o SELECT MATERIAL FOR MINIMUM RECOIL
- o MAXIMUM TENSION: 477 LBF (2122 N)
- o DESIGN FACTOR: 2.5 OR BETTER
- o LENGTH REQUIRED: 32.5 NMI (60 KM)
- o DESIGN FOR LENGTH RESERVE ON REEL OF 4%: 1.3 NMI (2.4 KM)
- o SELECTION
  - BRAIDED KEVLAR 49
  - DIAMETER 0.110 IN (2.79 KM)
  - ULTIMATE: 1250 LBF (5560 N)
  - MASS/LENGTH: 3.1 LBM/KFT (4.6 KG/KM)
  - TOTAL DEPLOYED MASS: 612 LBM (277 KG)

REEL

- o MAKE MAXIMUM UTILIZATION OF PLANNED TETHERED SATELLITE SYSTEM (TSS) HARDWARE. TSS REEL CAPACITY IS 110 NMI (204 KM) OF ABOVE TETHER .
- o TSS REEL DRIVE SYSTEM WILL REQUIRE MODIFICATION FOR DEPLOYMENT TENSION LOADS.

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Tether Dynamics

Simulation runs of the AXAF deployment were performed using the TETHDY program. These simulations indicated a sraightforward deployment with no complications.

The angular excursions observed were a maximum angle of 25 degrees at 32 minutes into the deployment, a peak of 13 degrees at 83 minutes, and 7 degrees at 152 minutes. Tension levels were still negligible at these times. After tension buildup had started the maximum excursion was 6 degrees at 250 minutes with a tension of 110 lb.

The deployed AXAF stabilized to a $\pm$ 3 degree limit of angular excursion about the vertical during the course of the 8 hour period for AXAF checkout. This was with no active control law damping in action and with the Shuttle in a 290 by 118 nmi elliptical orbit.

Tether dynamics subsequent to the release of AXAF need further study to define the tether recoil effects.

TETHER DYNAMICS

- o SIMULATION RUNS OF DEPLOYMENT (USING TETHDY PROGRAM) INDICATE NO DEPLOYMENT COMPLICATIONS.
- o IN-PLANE EXCURSION ANGLES:
  - MAX OF 25 DEGREES AT 32 MINUTES (TENSION NEGLIGIBLE)
  - 13 DEGREES AT 83 MINUTES (TENSION NEGLIGIBLE)
  - 7 DEGREES AT 152 MINUTES (TENSION NEGLIGIBLE)
  - 6 DEGREES AT 250 MINUTES (TENSION 110 LBF)
- o STABILIZES TO $\pm$ 3 DEGREE LIMIT DURING 8 HOUR CHECKOUT PERIOD.
- o TETHER DYNAMICS SUBSEQUENT TO AXAF RELEASE NEED FURTHER STUDY TO ASSURE ORBITER SAFETY.

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Functional Requirements

AXAF Attachment Grapple Fixture

- This fixture provides the single point release interface for the end effector.
- The fixture is to be located on the end of AXAF on the longitudinal centerline. It is assumed that the center-of-mass of AXAF is also on the centerline. If not the location of the fixture should be offset by the same amount so that it aligns. Otherwise AXAF will hang at a canted angle (which may be acceptable - TBD).
- The fixture will provide a load path for the tether tension loads into the AXAF structure.
- The fixture is to be attached to AXAF with pyrotechnic separation hardware that is commandable by ground control thru AXAF. This is to provide a backup release capability in the event the normal end effector release malfunctions.

End Effector

- Provides a single point attach/release mechanism under control of the Shuttle crew by means of a Ku band link.
- Interface with the AXAF grapple fixture.
- Incorporate a cold gas thruster system controlled from the Shuttle by means of a Ku band link. This system will provide the impetus to separate the AXAF from Shuttle and to effect the recovery of the tether and end effector after AXAF release. Cold gas is required to minimize contamination on AXAF.
- A Ku band transceiver and command decoder is required to control the release and the thruster system. Because of the restricted range of angles a small fixed horn antenna will be adequate.
- The estimated weight and volume of the end effector are not based on detailed analysis.

- o AXAF ATTACHMENT GRAPPLE FIXTURE
  - INTERFACES WITH END EFFECTOR ATTACH/RELEASE MECHANISM
  - LOCATED ON LONG AXIS OF SATELLITE
  - PROVIDES LOAD PATH FOR TENSION LOADS DURING DEPLOYMENT
  - ATTACHED TO AXAF BY PYROTECHNIC SEPARATION HARDWARE
  - ACTIVATION OF SEPARATION UNDER GROUND CONTROL AS BACKUP MODE

- o END EFFECTOR
  - SINGLE POINT ATTACH/RELEASE MECHANISM
  - RELEASE BY SHUTTLE CREW REMOTE CONTROL
  - INTERFACES WITH AXIAL GRAPPLE/FIXTURE ON AXAF
  - COLD GAS PROPULSION SYSTEM (INITIAL AXAF DEPLOYMENT, AND RETRIEVAL OF END EFFECTOR)
  - KU BAND TRANSCEIVER/DECODER WITH HORN ANTENNA (SHUTTLE COMMAND LINK)
  - TARGET MASS 1100 LBM (500 KG)
  - DIMENSION ENVELOPE: DIAMETER 3.3 FT (1 M), LENGTH 3.3 FT (1 M)

(CONT'D)

Functional Requirements

Tether

- Tether tension at maximum extension is 477 lbf (2122N) and the required length is 32.5 nmi (60 km).
- A design factor of 2.5 or better between working tension and ultimate.
- No requirement for tether reuse due to the three year interval between reboost operations for the AXAF.

Retrieval Boom

- The boom is required to effect the retrieval capture of the end effector. The objective is to translate the capture process outboard from the Shuttle.
- The mass of AXAF and the resulting tension will cause a bending moment in the boom used for retrieval of the end effector. The boom design must be capable of reacting these bending moment forces.

Tether Reel and Drive

- To the maximum extent possible utilize the hardware under development for the Tethered Satellite System program.
- The system is to be capable of providing the braking torque required to deploy the AXAF.
- Accommodate the energy generated during deployment of the AXAF. This energy must be dispositioned by either the Shuttle thermal control system or a dedicated radiator as a part of the system.
- The system must supply the energy required to retrieve the tether and end effector. This energy could be obtained from the Shuttle power system or from a dedicated power storage system.

- o TETHER
  - MAXIMUM TENSION: 477 LBF (2122 N)
  - LENGTH: 32.5 NMI (60 KM)
  - DESIGN FACTOR: 2.5 OR BETTER
  - NO REUSE - NO JACKET REQUIRED
- o RETRIEVAL BOOM (TSS SYSTEM)
  - FACILITATE END MASS RETRIEVAL
  - REACT TETHER TENSION LOADS
- o TETHER REEL AND DRIVE
  - USE TETHERED SATELLITE SYSTEM HARDWARE - MODIFY AS REQUIRED
  - PROVIDE BRAKING TENSION FOR AXAF DEPLOYMENT
  - ACCOMMODATE (DISPOSITION) ENERGY GENERATED DURING DEPLOYMENT
  - PROVIDE ENERGY REQUIRED TO RETRIEVE TETHER/END EFFECTOR

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AXAF Satellite and Deployer in Cargo Bay

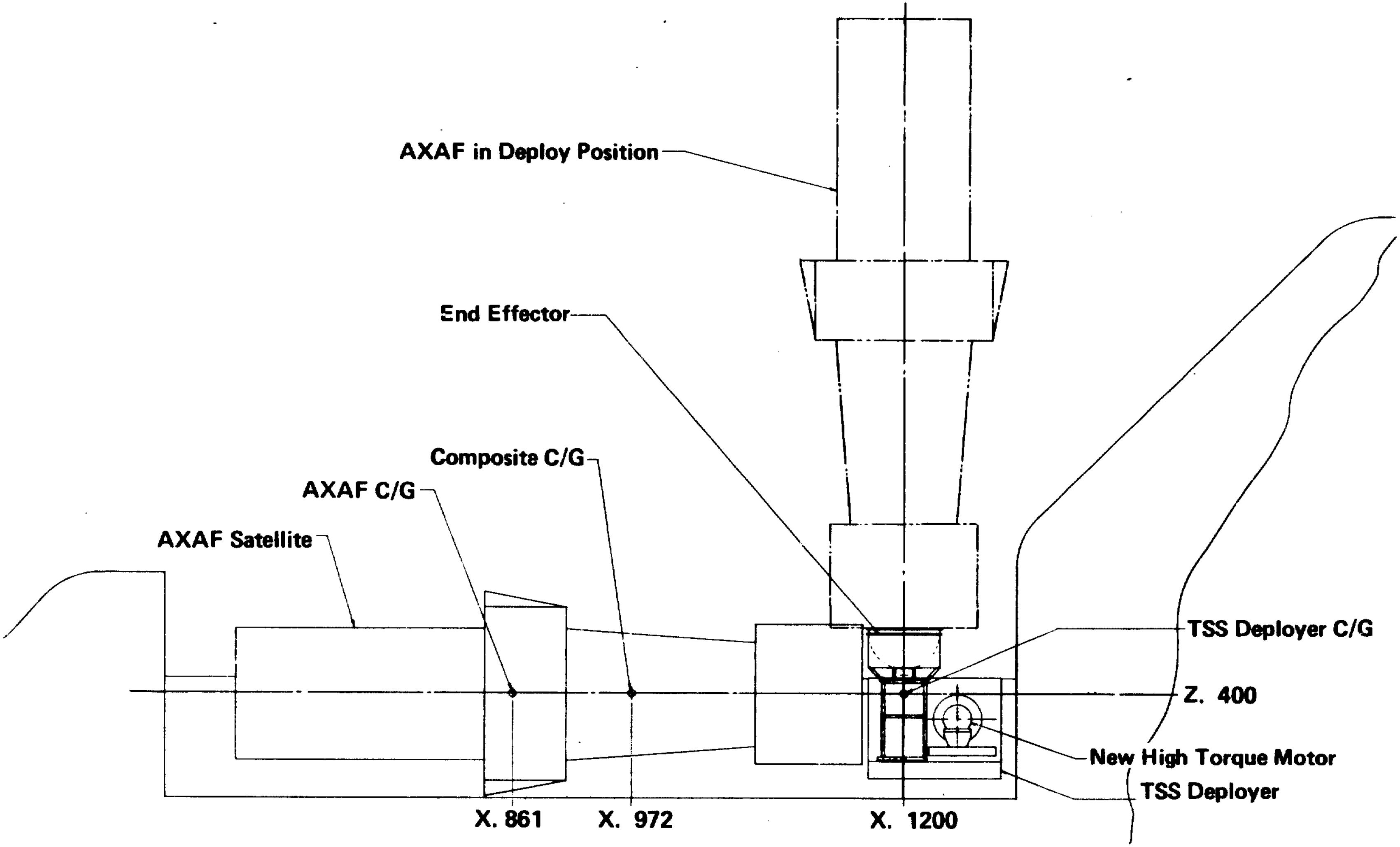
The AXAF satellite is positioned in the cargo bay as was shown in the AXAF industry briefing presentation package that was presented at Marshall Spacecraft Center November 9, 1982. That presentation included an OMS kit at the aft end. The OMS kit has been removed and replaced with a tethered satellite system deployer now being designed for late 1987 use.

To accommodate the high tension requirements of the AXAF boost mission, a larger reel motor has been incorporated.

The resultant combined CM is approximately the same as that shown in the industry briefing.

The AXAF is shown in phantom clamped to the end effector in preparation for deployment.

AXAF Satellite and Deployer in Cargo Bay

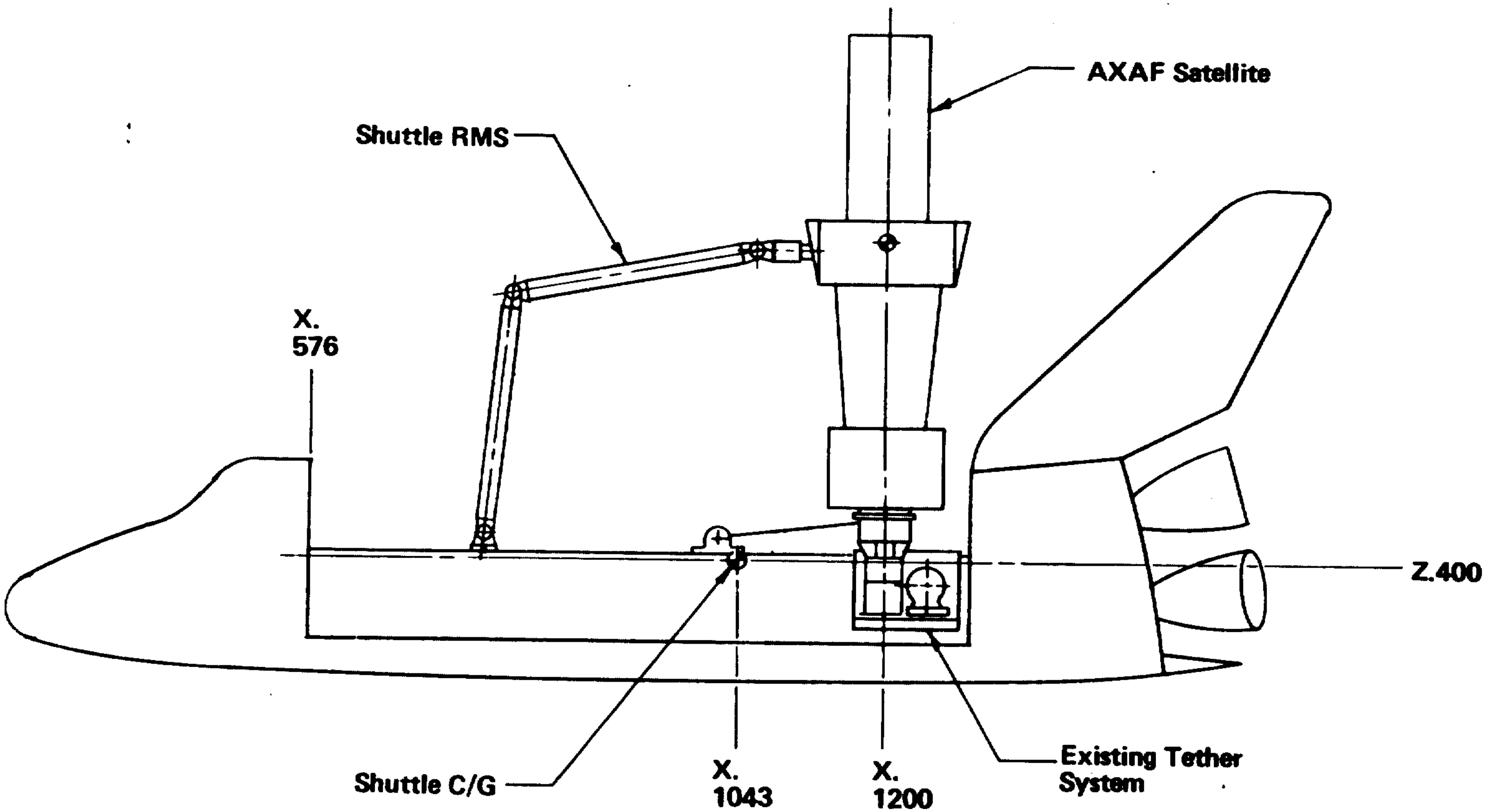


AXAF Positioned for Deployment

The AXAF satellite is shown being fixed to the end effector. The satellite is removed from the cargo bay by the shuttle remote manipulator arm and placed in position.

With the shift in position of AXAF the combined CM moves aft.

AXAF Positioned for Deployment



AXAF Deployed

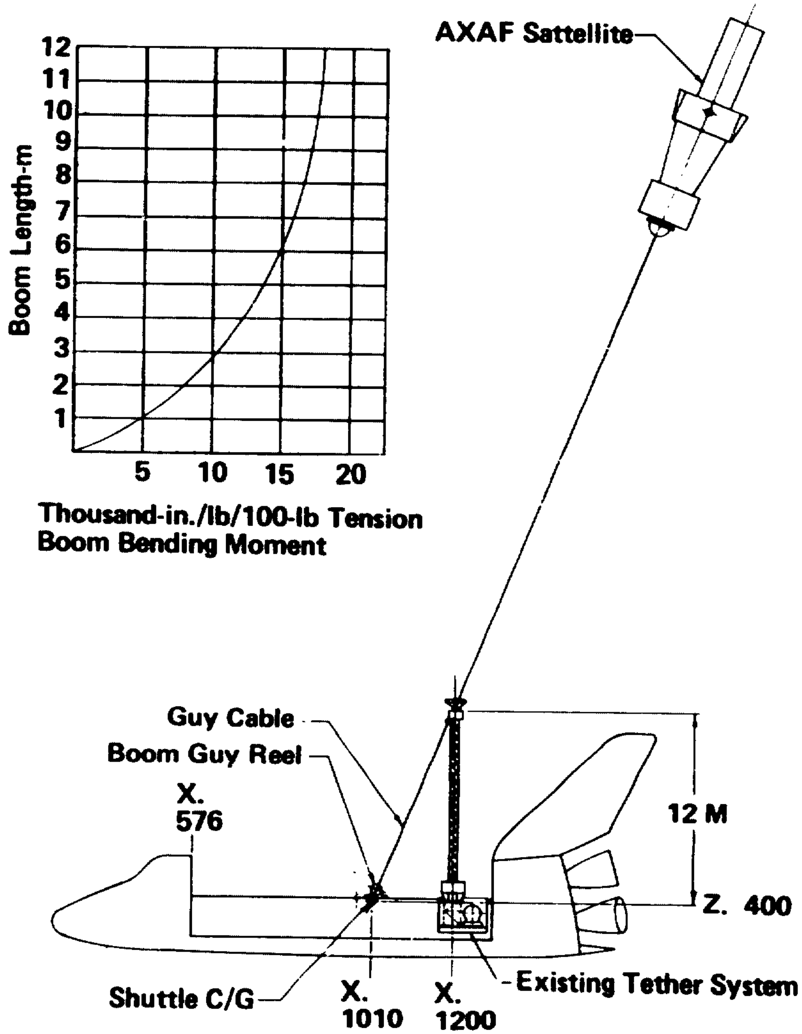
This figure describes the relationship of masses and centers of mass of the shuttle and AXAF satellite in deployed gravity gradient stabilized position. A straight line connecting the centers of mass pass thru the deployed boom tip. This imposes bending on the boom because the tether tension load is applied at an angle to the boom center line.

The boom is designed for an allowable 25,000 in-lb bending moment. The graph shows that with the boom fully extended (12 meters), the maximum tension the boom can react is $\frac{25,000}{18,000} \times 100 = 139$ pounds.

Due to the large mass of AXAF, the bending load allowable of the boom is exceeded. The addition of the guy cable will eliminate the boom bending problem . The guy cable is stored on a negator spring drum which will automatically pay out to an end stop and retract as the boom retracts.

After release of AXAF from the end effector, the end is retrieved and docked in the docking ring. The boom is then retracted to stow position and clamped in place for reentry.

AXAF Deployed



AXAF Deployed

Safety Considerations

The only significant safety concern identified for this concept is that associated, with a broken or severed tether occurring during the deployment of the AXAF. At this time the tether is under significant tension load. The elastic energy stored in the tether stretch could cause the broken end to recoil and pile up into the shuttle cargo bay.

This consideration was the reason for the selection of Kevlar 49 as the tether material because of the higher modulus (2 times Kevlar 29).

It should be emphasized that this is a conjectural concern at this time and in need of better data on recoil damping characteristics of actual tether specimens and on improved simulation modeling for tether behavior.

- TETHER RECOIL SUBSEQUENT TO A BREAK DURING AXAF DEPLOYMENT
  - POTENTIAL IMPACT OF TETHER ON SHUTTLE CARGO BAY

Areas Needing Further Study

The tether recoil characteristics need to be better understood to determine if there is a safety problem associated with a tether break. Better data is needed on tether characteristics and improved simulation capabilities are needed to predict detailed behavior of tethers under these conditions.

The acceptability of the proposed attachment fixtures for the tether end effector located on the AXAF centerline needs to be verified.

The degree to which AXAF initialization and checkout can be performed while still attached to the tether needs to be investigated. This capability would improve overall mission assurance if all spacecraft systems could be verified prior to final release. One specific concern area that has been identified is the effect of the tether induced acceleration levels (0.025g) on the deployed solar arrays and antennae.

Methods of accommodating the energy generated during the deployment will need to be determined. The energy is in the form of electrical power from the reel drive system operating in the braking mode. The total energy generated is 1.8 kWhr for the proposed deployment. A portion of it could be conditioned and used to charge a battery to be used for the subsequent retrieval of the end effector. However, most of it will probably need to be rejected as waste heat by means of a dedicated high temperature radiator.

The energy required to retrieve the tether end effector is of the same magnitude as the present TSS design requirement.

AREAS NEEDING FURTHER STUDY

- o TETHER RECOIL.
- o END EFFECTOR ATTACHMENT TO AXAF.
- o COMPATIBILITY OF AXAF WITH INITIALIZATION/CHECKOUT WHILE ON TETHER.
- o METHOD OF ACCOMMODATING DEPLOYMENT ENERGY BY TETHER SYSTEM.

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Technology Development

No unique technology development requirements have been identified for this concept.

- NONE IDENTIFIED

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AXAF Conventional Deployment with Shuttle

As recently envisioned in the cited MSFC reference, AFAX would be placed into a 320 nmi (593 km) circular orbit by a dedicated Shuttle flight via the direct orbit insertion technique. The selected orbit inclination is 28.5 degrees.

This method was preferred over the use of integral propulsion, an OMS kit on the Orbiter or OMV delivery. (Tether deployment was not investigated at this time).

The AXAF satellite will also require periodic revisits and reboosting of its orbit (typically, in 3 yrs).

AXAF CONVENTIONAL DEPLOYMENT WITH SHUTTLE

- *DEDICATED STS DELIVERY MISSION.
- DIRECT INSERTION TO 320 NMI (593 KM) CIRCULAR ORBIT.
- 28.5 DEGREE ORBIT INCLINATION.
- NO INTEGRAL PROPULSION ON AXAF.
- REQUIRES PERIODIC REVISITS AND REBOOST (TYPICALLY, IN 3 YRS).

* AXAF INDUSTRY BRIEFING BY MSFC, NOVEMBER 9, 1982.
PREFERRED OVER INTEGRAL PROPULSION, OMS KIT, OR OMV DELIVERY (TETHERED DEPLOYMENT NOT INVESTIGATED).

CONCLUSIONS

1. PLACEMENT OF AXAF INTO OPERATIONAL ORBIT CAN BE ACCOMPLISHED BY THE SHUTTLE EITHER BY DIRECT INSERTION OR BY TETHER INSERTION FROM A LOWER ALTITUDE.

2. AXAF REBOOST AFTER SERVICING CAN BE PERFORMED BY TETHER INSERTION. ALTERNATIVE METHOD REQUIRES A PROPULSION STAGE TO REBOOST.

3. TETHERED INSERTION SAVES SEVERAL THOUSAND POUNDS OF OMS PROPELLANT.

4. EITHER METHOD REQUIRES A DEDICATED SHUTTLE FLIGHT.

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RECOMMENDATIONS

1. TETHERED INSERTION OF AXAF IS RECOMMENDED AS A BACKUP MODE TO DIRECT INSERTION IN THE EVENT PERFORMANCE IS MARGINAL IN THE DIRECT INSERTION MODE.

2. INVESTIGATE THE POSSIBILITY OF UTILIZING THE EXTRA SHUTTLE PERFORMANCE AVAILABLE IN THE TETHERED MODE TO CARRY ADDITIONAL CARGO.

3. INVESTIGATE UTILIZATION OF A TETHER FOR THE NECESSARY PERIODIC (3 YEAR) REBOOSTING OF AXAF DURING ITS LIFETIME.

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SECTION C

AN OPERATIONAL SCIENCE/TECHNOLOGY PLATFORM TETHER DEPLOYED FROM SPACE STATION.

Concept Definition

A multimission capability tethered platform designed to operate from the Space Station was selected for analysis. This approach results in a modularized platform which can be adapted to host a variety of operational missions.

Typical missions which could be accommodated are a variety of observational sciences such as astronomy, astrophysics, solarphysics, space sciences, and magnetospheric studies. Materials processing investigations and some forms of life sciences studies could also be accommodated.

In order to focus this study on a specific set of objectives an observatory class cryogenically cooled IR telescope was selected as the mission payload to be analyzed.

The concept was developed to a modularized approach for the tethered platform comprising 3 modules:

a. Payload/Instrument
b. Subsystem
c. End Effector

The combination of instrument and subsystem modules are considered to be mission dedicated hardware and to be sized such that they can be transported to orbit as a single assembly in the shuttle cargo bay. The system has been sized to provide generous capacity to the mission. Mass allocation: 30,000 lbm (13,636 kg).

The end effector will be a tether system dedicated item which will serve a variety of payloads.

The subsystem module can also be adapted to a variety of missions but it would require ground integration for each mission.

- A MULTIMISSION-CAPABLE TETHER-DEPLOYED PLATFORM TO OPERATE FROM THE SPACE STATION.
- MISSION CAPABILITY TO INCLUDE OBSERVATIONAL SCIENCES, MATERIALS PROCESSING, LIFE SCIENCES.
- FOR STUDY PURPOSE - PAYLOAD TO BE AN OBSERVATORY CLASS CRYO COOLED IR TELESCOPE.
- PAYLOAD REQUIREMENTS
  - NON-CONTAMINATING OPERATING ENVIRONMENT
  - CRYOGEN RESUPPLY AT 6 MONTH INTERVALS
  - PERFORM TARGET TRACKING AND FINE POINTING
  - ACCESS RANGE TO CELESTIAL SPHERE OVER REGION AFT OF VERTICAL PLANE PERPENDICULAR TO ORBIT PATH AND TO WITHIN 10 DEGREES OF HORIZON
  - TELESCOPE MASS: 6600 LBM (3000 KG)
  - DIAMETER: 6.5 FT (2M), LENGTH: 26 FT (8M)
- TETHER DEPLOYED PLATFORM TO COMPRISE 3 MODULES
  - PAYLOAD/INSTRUMENT
  - SUBSYSTEM
  - END EFFECTOR
- CONSIDER THE COMBINATION OF INSTRUMENT AND SUBSYSTEM MODULE TO BE MISSION DEDICATED.
- END EFFECTOR TO BE TETHER SYSTEM DEDICATED.

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Ground Rules and Assumptions

Platform routine operations are to be managed by ground control via a TDRS link to Space Station and from the station to the platform. This is analogous to the planned operating mode for observatory facility free flyers and for the Space Station free flyer platforms.

The station crew will be responsible for deployment, retrieval, and servicing of the platform subsystems and payload elements.

Because of the extended operation times the probability of a severed tether is increased. Since no method is available to prevent a severed tether the system must be capable of surviving such a contingency and of being rescued by either an OMV or OTV mission.

The platform power system shall be autonomous to the platform to avoid any requirement for conductive elements in the tether. Potential of the order of 1700 volts would be generated by such elements and could require special provisions to prevent potential differences between the Space Station and the ambient plasma potential.

The platforms are to be designed to operate for 6 months or longer between servicing.

In the event orbiter docking and departure operations cause perturbations to the platform stability, the platform will go to a standby mode until stable conditions are re-established.

The platform will be earth oriented and stabilized about three axes. The instrument/payload will provide any required pointing, target tracking or fine control pointing required.

GROUND RULES AND ASSUMPTIONS

- PLATFORM OPERATIONS TO BE MANAGED BY GROUND CONTROL VIA TDRS LINK THROUGH SPACE STATION. THIS INCLUDES OBSERVATORY OPERATIONS AND SUBSYSTEM MANAGEMENT.
- TETHER SYSTEM OPERATIONS BY THE SPACE STATION CREW. THIS INCLUDES DEPLOY, LIBRATION DAMPING, RETRIEVAL, SERVICING.
- IN EVENT OF BROKEN TETHER, PLATFORM TO BE CAPABLE OF SURVIVAL IN FREE FLYER MODE AND SUBSEQUENT RESCUE BY OMV OR SHUTTLE RENDEZVOUS.
- PLATFORM POWER SYSTEM TO BE AUTONOMOUS TO PLATFORM. NO CONDUCTIVE ELEMENTS IN TETHER TO AVOID ELECTRODYNAMICALLY INDUCED VOLTAGES (1700 VOLTS).
- SIX MONTH INTERVALS BETWEEN SERVICING.
- PLATFORM OPERATIONS WILL GO TO STANDBY (IF REQUIRED) DURING ORBITER RENDEZVOUS OPERATIONS WITH THE STATION.
- ALL REQUIRED TARGET TRACKING AND FINE POINTING TO BE PROVIDED BY MISSION DEDICATED EQUIPMENT.
- PLATFORM WILL PROVIDE YAW CONTROL ABOUT THE TETHER AXIS.

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Operations Concept

This viewgraph indicates the major sequence steps in operating a typical tethered platform.

1. MISSION HARDWARE (INTEGRATED PAYLOAD AND SUBSYSTEM MODULES) DELIVERED TO STATION BY SHUTTLE.
2. USING THE STATION RMS, THE STATION CREW TRANSFERS THE MISSION HARDWARE TO THE TETHER SYSTEM BERTHING AREA AND MATES IT WITH THE TETHER SYSTEM END EFFECTOR.
3. PERFORM CHECKOUT OF INTEGRATED PLATFORM.
4. RELEASE END EFFECTOR FROM BERTHING LATCHES AND INITIATE TETHER DEPLOYMENT USING THE END EFFECTOR THRUSTERS FOR INITIAL SEPARATION (ESTIMATED AT 1 KM).
5. CONTINUE DEPLOYMENT USING GRAVITY GRADIENT FORCE TO FULL TETHER LENGTH (10 KM) AND STABILIZE PLATFORM.
6. GROUND CONTROL OF PLATFORM INITIATED AND PLATFORM INITIALIZATION AND CHECKOUT PERFORMED.
7. PLATFORM OPERATIONS INITIATED UNDER GROUND CONTROL (VIA TDRSS LINK THRU SPACE STATION). STATION CREW REVERTS TO STANDBY MODE.
8. OPERATIONS INTERVAL - 6 MONTH GOAL.
9. GROUND CONTROL SECURES PLATFORM FOR RETRIEVAL.
10. STATION CREW PERFORMS PLATFORM RETRIEVAL (USING END EFFECTOR THRUSTERS FOR CLOSE-IN CONTROL) AND BERTHING.
11. STATION CREW PERFORMS RESUPPLY/SERVICING.
12. REVERT TO 3 AND REPEAT.

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Orbit Considerations

This concept is an example of a tethered constellation operated in stable orbit conditions. The Space Station will be at a nominal orbit altitude of 270 nmi (500 km). For a platform at the upper limit of mass (31,100 lbm) the ratio of platform to station mass is approximately 1 to 10. With the platform deployed the system center-of-mass will be 0.9 km above the station.

Again under these maximum platform mass conditions the station will experience acceleration levels up to $3 \times 10^{-4}g$ and the platform up to $3.5 \times 10^{-3}g$.

ORBIT CONSIDERATIONS

- SPACE STATION IN A NOMINAL 270 NMI (500 KM) CIRCULAR ORBIT.
- PLATFORM TETHER DEPLOYED TO 5.4 NMI (10 KM) ABOVE STATION.
- AT MAXIMUM PLATFORM MASS OF 31,100 LBM (14,136 KG) THE STATION WILL BE 0.9 KM BELOW THE SYSTEM CM.
- THE INDUCED ACCELERATION ON THE STATION WILL NOT EXCEED 3.7×10^{-4}G.
- THE INDUCED ACCELERATION ON THE PLATFORM WILL NOT EXCEED 3.5×10^{-3}G.

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Tether System Design Considerations

The system functional requirements allocations are to be based on a three module concept for the platforms as follows:

> End Effector Module - This module is to incorporate those functions that are essential to the operation of the tethered system and are common to all varieties of platform missions. This module will be considered as a part of the tether system.
>
> Subsystem Module - This module is to incorporate subsystem support functions of a general mission nature. This module is to be considered part of the mission dedicated hardware, but one which could be adapted to support other missions.
>
> Payload/Instrument Module - This module is unique to the selected mission and incorporates specialized functions.

The end effector will incorporate a cold gas propulsion system to effect deployment and retrieval operations. The propulsion system will be deactivated during operations periods to minimize contamination environment for the payload.

The tether tension will provide stabilization about the horizontal axes.

The platform will provide yaw control stabilization (about the tether axis).

Power supply subsystem will be autonomous to the platform to avoid conductive tether.

The platforms shall have the inherent capability to survive as a free flyer in event of a broken tether. This shall include the capability to jettison the broken tether end and to be compatible with rendezvous rescue missions by OMV or Shuttle.

Routine operation of the platform is to be managed by ground control through a TDRS relay link to the Space Station and then to the platform.

The tension force is to be capable of being aligned to the station center-of-mass both with and without the Shuttle present at the station.

Berthing provisions for the platform are to be provided at the station to perform servicing operations.

TETHER SYSTEM DESIGN CONSIDERATIONS

- 3 MODULE PLATFORM
  - END EFFECTOR (TETHER SYSTEM ELEMENT)
  - SUBSYSTEM (MISSION ADAPTED ELEMENT)
  - PAYLOAD/INSTRUMENT (MISSION DEDICATED)
- COLD GAS PROPULSION SYSTEM
  - DEPLOY/RETRIEVE
  - DEACTIVATE DURING OPERATIONS
- STABILIZATION
  - TETHER TENSION MOMENT FOR X AND Y AXES
  - YAW CONTROL (ABOUT TETHER OR Z AXIS) BY PLATFORM
- AUTONOMOUS POWER SYSTEM.
- SURVIVAL CAPABILITY FOR BROKEN TETHER CONTINGENCY.
- OPERATIONS UNDER GROUND CONTROL.
- TENSION ALIGNMENT WITH AND WITHOUT SHUTTLE AT STATION.
- BERTHING/SERVICING PROVISION AT STATION.

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Tether Dynamics

The tether dynamics associated with deployment and retrieval of the platform are felt to be well understood.

Extended simulation runs were made to determine equilibrium libration rates both with and without active control law damping. The object was to determine platform behavior without active damping as this mode would be preferable for extended operations periods.

Application of active damping made very little difference in the equilibrium limits on libration rates. Actual values were:

With damping: less than 2.4×10^{-3} degrees/hour
Without damping: less than 3.0×10^{-3} degrees/hour

The out-of-plane libration rates range from 10^{-7} to 10^{-5} degrees/hour.

Shuttle docking and undocking produced no detectable change in the libration rates. It should be noted that these docking operations consisted of adding or subtracting the Shuttle mass to the Space Station. No attempt was made to include any docking impact.

- DYNAMICS ASSOCIATED WITH DEPLOYMENT AND RETRIEVAL OPERATIONS ARE CONSIDERED ROUTINE.
- SIMULATION RUNS INDICATE ANGULAR RATES OF LESS THAN 3×10^{-3} DEGREES PER HOUR FOR THE IN-PLANE LIBRATION AND LESS THAN 10^{-5} FOR OUT-OF-PLANE.
- THESE RATES WERE WITHOUT ACTIVE DAMPING BY THE REEL DRIVE.
- SHUTTLE DOCKING AND UNDOCKING SIMULATION INDICATED NEGLIGIBLE EFFECTS ON LIBRATION RATES.

Functional Requirements

The concept for this study will comprise three major modules in the deployed platform. This approach has been used to provide the maximum flexibility in adapting to a variety of mission requirements for the platform.

The end effector module will encompass all functional requirements common to all missions that are an inherent part of the tether platform concept no matter what mission is undertaken.

The subsystem module is mission oriented and will require adaptation to the particular mission, however, it is intended to provide functions of a somewhat general nature that would be appropriate for a variety of different platform missions.

The payload/instrument module contains those functional elements that are clearly mission peculiar, and is a mission dedicated hardware element.

The mission selected for this concept study is an observatory class cryogenically cooled IR telescope.

The end effector has been allocated the functional requirements listed.

FUNCTIONAL REQUIREMENTS

- o TETHERED PLATFORM COMPRISES THREE MODULES:
  - END EFFECTOR (TETHER SYSTEM ELEMENT)
  - SUBSYSTEMS (MISSION TYPE ELEMENT)
  - PAYLOAD/INSTRUMENT (MISSION DEDICATED)
- o PARTICULAR PAYLOAD SELECTED - CRYO COOLED OBSERVATORY CLASS IR TELESCOPE
- o END EFFECTOR MODULE
  - TARGET MASS 1100 LBS (500 KG)
  - PROVIDE COLD GAS PROPULSION SYSTEM FOR DEPLOY/RETRIEVE AND FOR ACS FUNCTIONS IN CONTINGENCY RECOVERY MODE
  - KU BAND COMMUNICATIONS LINK WITH SPACE STATION (CONTROL, HOUSEKEEPING, DATA RETURN)
  - OMNI KU BAND ANTENNA FOR CONTINGENCY RECOVERY MODE (COMMANDS TO TETHER GUILLOTINE, PLATFORM ACS, SUBSYSTEMS VIA TDRS LINK FROM GROUND)
  - RETROREFLECTOR(S) FOR SPACE STATION RADAR TRACKING OR FOR SHUTTLE RADAR IN CONTINGENCY MODE
  - INTERFACE WITH SERVICING BERTH ON SPACE STATION
  - ADJUSTABLE TETHER ATTACH POINT WITH GUILLOTINE (UNDER GROUND CONTROL VIA TDRS)
  - INTERFACE WITH SUBSYSTEM MODULE

(CONT'D)

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Functional Requirements (Continued)

Subsystem Module

The subsystem module has been allocated the listed functional requirements. The autonomous power system was designated to avoid the problems associated with conductive elements in the tether, which would be required to use station power. A magnetic torquer system was selected to provide yaw control torque in order to provide a contamination free environment for the cooled surfaces of the telescope. The requirement to provide Shuttle interfaces was also allocated to this module to simplify design requirements for the payload module.

Payload/Instrument Module

Payload peculiar requirements such as target pointing, tracking and fine pointing control have been allocated to this mission dedicated module. In addition such functions as environmental protection during launch and retrieval have been allocated here. Payload peculiar servicing interfaces are assigned to this module also.

Tether

Required tether characteristics are identified.

- o SUBSYSTEM MODULE
  - POWER SUBSYSTEM (ENERGY CONVERSION, STORAGE, CONDITIONING, DISTRIBUTION)
  - THERMAL CONTROL (AS REQUIRED)
  - MAGNETIC TORQUER SYSTEM FOR YAW CONTROL ABOUT TETHER AXIS
  - PROVIDES STS INTERFACE FOR TRANSPORT OF PAYLOAD MODULE
  - INTERFACES WITH END EFFECTOR MODULE
  - INTERFACES WITH PAYLOAD MODULE
- o PAYLOAD/INSTRUMENT MODULE (TYPICAL)
  - PROVIDES TRACKING AND FINE POINTING SYSTEM FOR OBSERVATORY TELESCOPE
  - INSTRUMENT DATA PROCESSING (AS REQUIRED)
  - ENVIRONMENTAL PROTECTION FOR LAUNCH, DEPLOY, RETRIEVE, SERVICING, AND RETURN TO EARTH PHASES
  - INTERFACES WITH SERVICING FACILITIES ON SPACE STATION (CRYO RESUPPLY)
- o TETHER
  - DEPLOYED LENGTH: 5.4 NMI (10 KM), RESERVE ON REEL: 0.5 NMI (1 KM)
  - MATERIAL KEVLAR 29 WITH PROTECTIVE TEFLON BRAID JACKET
  - KEVLAR DIAMETER: 0.110 INCH (2.8 MM)
  - JACKETED DIAMETER: 0.130 INCH (3.3 MM)
  - ULTIMATE: 1250 LBF (5562 N)
  - WORKING TENSION: 110 LBF (490 N)
  - CONTINUOUS EXPOSURE TO SPACE ENVIRONMENT (5 YEAR LIFE)

(CONT'D)

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Functional Requirements

Tether Reel and Drive

The allocated requirements are identified. The deployment energy generated is relatively modest and should not present a problem. The capability to implement damping control laws is stated although initial analyses indicate a good quality of stability even with the reel fixed in position.

The reel drive will utilize station power and it will incorporate a guillotine device under control of the station crew to sever the tether in event of an emergency.

Tension Alignment Mechanism

This mechanism is required to align the tether tension force to the station center-of-mass both with and without the Orbiter present at the station.

Platform Berthing Facility

This capability must be integrated with the alignment mechanism above to facilitate the servicing operations of the platform.

FUNCTIONAL REQUIREMENTS (CONTINUED)

- TETHER REEL AND DRIVE
  - CAPACITY 5.9 NMI (11 KM) OF ABOVE TETHER
  - PROVIDE CAPABILITY TO ACCOMMODATE DEPLOYMENT ENERGY (0.7 KWH)
  - PROVIDE REEL IN/OUT CAPABILITY TO IMPLEMENT CONTROL LAWS
  - PROVIDE PLATFORM RETRIEVAL REEL-IN
  - UTILIZE SPACE STATION POWER FOR REEL
  - INCORPORATE TETHER GUILLOTINE UNDER CONTROL OF STATION CREW
- TENSION ALIGNMENT MECHANISM
  - PROVIDE CAPABILITY TO ALIGN TETHER TENSION WITH SPACE STATION CM
  - CAPABILITY TO ADJUST FOR SHUTTLE PRESENCE DOCKED TO STATION
  - LOCATED ON ZENITH OF STATION WITH NO TETHER OBSTRUCTIONS
- PLATFORM BERTHING FACILITY
  - STRUCTURAL TIEDOWN FOR RETRIEVED PLATFORM DURING SERVICING AND MAINTENANCE OPERATIONS
  - INTERFACE WITH TETHER END EFFECTOR
  - INTERFACE WITH SERVICING/RESUPPLY SYSTEMS (E.G., CRYOGEN RESUPPLY SYSTEM - TBD
  - ACCESSIBLE BY STATION RMS

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Gravity Gradient Tethered Platform from Space Station

The tethered platform is a modularized system made up of three principle sections: The end effector, subsystem module and instrument section.

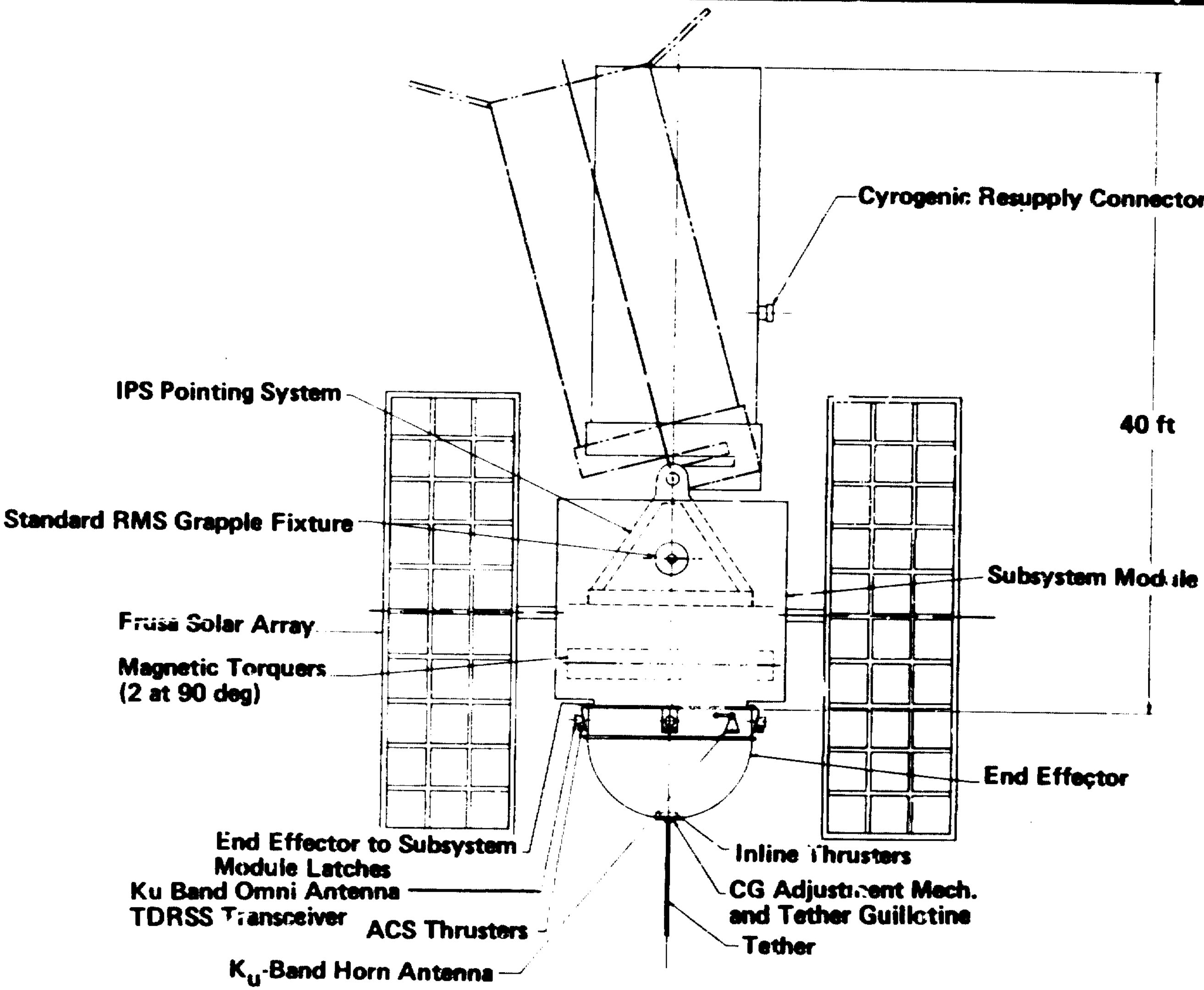
The end effector will provide all systems required for deployment and retrieval, propulsion system, communications and tracking, tether guillotine and center-of-mass adjustment mechanism.

The subsystem module latches to the end effector and will utilize a universal interface for a number of payloads. It will supply all power and yaw attitude control.

An RMS grappler fixture will allow for retrieval by shuttle or OMV in case of tether failure.

An infrared telescope is shown as a candidate instrument mounted on an IPS pointing system. For this system a cryo resupply connector is shown.

Gravity Gradiant Tethered Platform from Space Station



Safety Considerations

No unique safety hazards have been identified for this concept.

The elastic energy stored in the tether is insignificant and not considered a problem in the event of tether break.

Recovery of the platform subsequent to a broken tether should be a routine operation for either the OMV or shuttle. Platform safing operations would be performed by ground control via TDRS. Platform systems have been conceived to be autonomous and capable of survival of such a contingency.

Disposition of broken tether ends which have been severed by guillotine are a residual concern.

The presence of the tethered platform on a continuous basis does present a navigation hazard for station proximity operations, however, this is not considered to be a safety consideration in the context of this analysis.

SAFETY CONSIDERATIONS

- NONE IDENTIFIED

MARTIN MARIETTA

Areas Needing Further Study

The stability characteristics of a tethered platform with magnetic torques for yaw control needs to be analyzed in more detail to define the control achievable.

The platform will be perturbed by routine station operations such as shuttle docking and separation. The resulting effects and settling times need to be determined in more detail.

The accommodation of a tethered platform into the proximity operations concepts for Space Station should be studied.

In the event of a broken tether the platform would become the equivalent of a free flying platform. Detailed rendezvous and capture analyses should be performed to insure compatibility with OMV and/or shuttle recovery capabilities.

The tether exposure for extended operation periods with periodic retrieval and redeploy require a level of durability in the space environment that is unique to this concept. Long term effects of erosion by residual atmosphere must be understood and protective measures adopted.

The payload selected for this analysis requires a periodic resupply of liquid helium. No such systems are currently under development to the best of our knowledge.

AREAS NEEDING FURTHER STUDY

- o PLATFORM STABILITY CHARACTERISTICS.
- o EFFECTS ON PLATFORM FROM STATION OPERATIONS (E.G, SHUTTLE DOCKING).
- o PROXIMITY OPERATIONS INTERFERENCE.
- o CONTINGENCY RECOVERY OPERATIONS FOR ADRIFT PLATFORM.
- o TETHER DURABILITY.
- o CRYO RESUPPLY SYSTEMS DEFINITION.

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Technology Development

Tether deployed platforms generate a new tether durability requirement. The primary consideration is resistance to the erosive effects of residual atmosphere (e.g., atomic oxygen). It would seem reasonable to hope for tether life times of 5 to 10 years between changeout.

The probability of a tether suffering damage from micrometeorite or debris impact increases with exposure time, but there seems to be little that can be done to prevent a tether break other than design for platform recovery. Redundant tethers have been considered but ruled out as operationally impractical.

Fiber optic channels could conceivably be incorporated into the tether construction to provide redundant communication channels. They would not replace the microwave channels because of the requirement for control and recovery after a tether break.

The selected payload for this analysis would require periodic cryogen resupply. The cryogen of choice is liquid helium. Definition is needed of the method to perform such resupply.

TECHNOLOGY DEVELOPMENT

- o LONG TERM EXPOSURE TETHERS.
- o FIBER OPTIC INCORPORATED INTO TETHER.
- o CRYOGEN RESUPPLY TECHNOLOGY (INSTRUMENT CRYOGENS).

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Free Flying Co-Orbiting Platform

The benefits and techniques associated with free-flying platforms co-orbiting in the vicinity of the Space Station are discussed in the cited reference. The basic benefit is to have a platform which is easily accessible from the Space Station (via OMV) at periodic intervals but is not adjacent to other Space Station activities, contaminants, and disturbances.

The Shuttle or OMV would normally deliver the operational platform to its desired location. The orbit of the platform is typically a few nautical miles above or below the Space Station orbit and slightly out of plane. The orbiting arrangement can be set such that the platform moves from tens of nautical miles in front of the Space Station to a similar distance behind it in a relative orbit around the Space Station.

The OMV can periodically be sent out from the Space Station to accomplish delivery, servicing, or retrieval missions at the platform. (The orbit is preselected to have the desired visit intervals to correspond to minimum OMV fuel requirements). Rendezvous and docking at the platform will normally be required for each mission.

The position of the platform, relative to the Space Station, must be controlled by on-board propulsion frequently to overcome the differential drag and earth oblateness effects between the platform and the Space Station and must also respond whenever the Space Station has a major orbit stationkeeping correction or orbit disturbance.

- *SHUTTLE OR OMV DELIVERS OPERATIONAL PLATFORM TO LOCATION.
- THE ORBIT OF THE PLATFORM IS TYPICALLY A FEW NMI ABOVE OR BELOW THE SPACE STATION AND SLIGHTLY (SMALL FRACTION OF A DEGREE) OUT OF PLANE.
- THE ORBITING ARRANGEMENT CAN BE SET SUCH THAT THE PLATFORM MOVES FROM TENS OF NMI IN FRONT OF THE SPACE STATION TO A SIMILAR DISTANCE BEHIND IT IN A RELATIVE ORBIT AROUND THE SPACE STATION.
- THE OMV CAN PERIODICALLY BE SENT OUT FROM THE SPACE STATION TO ACCOMPLISH DELIVERY, SERVICING, OR RETRIEVAL MISSIONS AT THE PLATFORM. RENDEZVOUS AND DOCKING REQUIRED.
- THE RELATIVE POSITION OF THE PLATFORM MUST BE ACTIVELY CONTROLLED BY ON-BOARD PROPULSION FREQUENTLY TO OVERCOME DIFFERENTIAL DRAG AND EARTH OBLATENESS EFFECTS BETWEEN THE PLATFORM AND SPACE STATION AND MUST ALSO RESPOND WHENEVER THE SPACE STATION DOES A MAJOR ORBIT STATIONKEEPING CORRECTION.

* JOSEPH F. LOFTUS, JR., JOHNSON SPACE CENTER, ADVANCED MISSIONS DISCUSSIONS, AT MARTIN-MARIETTA DENVER, 16 NOVEMBER 1982.

CONCLUSIONS

1. A TETHERED PLATFORM APPEARS TO HAVE ADEQUATE STABILITY TO SERVE AS AN OBSERVATORY PLATFORM FOR PAYLOADS REQUIRING TRACKING AND FINE POINTING.
2. RETRIEVAL OPERATIONS FOR SERVICING AND MAINTENANCE ARE RELATIVELY SIMPLE.
3. THE PLATFORM CONCEPT IS ADAPTABLE TO A VARIETY OF MISSION APPLICATIONS.
4. MOST ENVIRONMENTAL BENEFITS AVAILABLE TO FREE-FLYING PLATFORMS ARE ALSO AVAILABLE TO TETHERED PLATFORMS.
5. PLATFORM MISSIONS MUST BE COMPATIBLE WITH ACCELERATION LEVELS INHERENT WITH TETHERED OPERATION.

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RECOMMENDATIONS

1. DEVELOP RANGE OF CANDIDATE MISSION APPLICATIONS.
2. INCREASE DEPTH OF ANALYSIS INTO TETHERED PLATFORM CONCEPTS AND OPERATIONS.
   - PLATFORM STABILITY
   - PLATFORM DESIGN
   - LOOSE PLATFORM RECOVERY OPERATIONS

MARTIN MARIETTA

SECTION D

TETHER MEDIATED RENDEZVOUS - AN OVM TETHER DEPLOYED FROM SPACE STATION TO RENDEZVOUS WITH AN AERO-BRAKED OTV RETURNING FROM A PAYLOAD DELIVERY MISSION.

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Concept Definition

For this concept the Space Station based Orbital Maneuvering Vehicle (OMV) is used in a tethered mode (TOMV) to actively accomplish final rendezvous and docking with the reusable - aerobraked Orbital Transfer Vehicle (OTV) returning from a high energy mission. The TOMV is tethered below the Space Station for this application. This will permit capture and rendezvous with the OTV at the apogee of its upcoming transfer orbit.

The method allows accomplishment of rendezvous and docking at a safe distance from the Space Station with retrieval of the TOMV/OTV stack by tether. OMV propellant requirements are expected to be reduced for each OTV retrieval mission, permitting more OMV flights. OTV propellant requirements are also reduced.

- USE A TETHERED ORBITAL MANEUVERING VEHICLE (TOMV) TO ACTIVELY ACCOMPLISH FINAL RENDEZVOUS AND DOCKING WITH THE REUSABLE AERO-BRAKED ORBITAL TRANSFER VEHICLE (OTV) RETURNING FROM A HIGH ENERGY MISSION. TOMV IS TETHERED BELOW THE SPACE STATION.
- ANGULAR MOMENTUM WILL BE TRANSFERRED FROM THE SPACE STATION TO THE TOMV AND OTV PERMITTING CAPTURE AND RENDEZVOUS WITH THE OTV AT THE APOGEE OF ITS TRANSFER ORBIT.

OBJECTIVES

- ACCOMPLISH RENDEZVOUS AND DOCKING AT A SAFE DISTANCE FROM THE SPACE STATION AND RETRIEVE THE TOMV/OTV STACK BY TETHER.
- REDUCE OMV PROPELLANT REQUIREMENTS FOR EACH OTV RETRIEVAL MISSION PERMITTING MORE OMV FLIGHTS. OTV PROPELLANT REQUIREMENTS ARE ALSO REDUCED.

Ground Rules and Assumptions

All calculations are based on an assumed Space Station mass of 300 klb (136,100 kg), a departing tethered OMV mass of 6.0 klb (2,727 kg). The TOMV carries a 1 klb (454 kg) propellant load and the returning OTV has no payload, but some remaining propellant.

The Space Station is initially assumed to be in a 270 nmi (500 km) circular orbit at a 28.5 degree orbit inclination. The OTV is assumed to be transferred up from a 220 nmi (407 km) circular phasing orbit prior to the time of rendezvous. The tether separation distance is selected at a point below the Space Station which will match the TOMV velocity with the apogee velocity of the OTV.

The intent is to utilize the planned OMV capabilities to the greatest extent. There is no plan to make any modifications to the OMV which would compromise its performance in a free-flying mode.

The OTV, through its GPS receiver data will provide location information to the Space Station. OTV mid-course maneuvers will be used during the orbit transfer phase to allow the TOMV to rendezvous and dock with the OTV. During the final rendezvous period, the OTV will maintain an attitude hold mode with its capture probe and docking interface oriented toward the TOMV.

GROUND RULES AND ASSUMPTIONS

PRIMARY MASSES

- o SPACE STATION: 300 KLBM (136,100 KG)
- o OMV (TETHERED): 6.3 KLBM (2,858 KG), INCLUDES 1 KLBM (454 KG) PROPELLANT LOAD
- o OTV (AEROBRAKED): 6.0 KLBM (2727 KG)

ORBITS

- o SPACE STATION AT 270 NMI (500 KM) CIRCULAR ORBIT AT 28.5 DEGREE INCLINATION.
- o OTV IN AN ASCENDING ORBIT FROM A 220 NMI (407 KM) CIRCULAR PHASING ORBIT.
- o SELECT TETHER SEPARATION DISTANCE BELOW THE SPACE STATION WHICH WILL MATCH THE TOMV VELOCITY WITH THE APOGEE VELOCITY OF THE OTV.

OMV

- o UTILIZE THE PLANNED OMV CAPABILITIES AND DO NOT PLAN MODIFICATIONS WHICH WOULD COMPROMISE OMV PERFORMANCE IN FREE FLYING MODE.

OTV

- o PROVIDES GPS LOCATION INFORMATION TO SPACE STATION.
- o MIDCOURSE MANEUVERS WILL BE UTILIZED TO EFFECT RENDEZVOUS.
- o ATTITUDE HOLD CAPABILITY.
- o COMPATIBLE CAPTURE PROBE AND DOCKING INTERFACE TO OMV.

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Operations Concept

Using EVA, install the support sling on the OMV and attach it to the tether.

Disengage the TOMV docking latches and initiate tether deployment by maneuvering the TOMV away from the Space Station with the slack tether trailing.

At 1-2 Km below the Space Station discontinue active thrusting for tether tensioning and continue deployment with gravity gradient forces. At the specified tether length stop deployment and stabilize the TOMV system. The TOMV will be transferred to the automatic rendezvous mode at the appropriate time (TBD min.) before OTV intercept, until final docking is complete.

The OTV will maintain attitude hold until capture and final docking is completed. At that time attitude control will be assumed by the TOMV. After docking, the tether will be re-stabilized and tether retrieval will be initiated.

Retrieval will be continued (with active TOMV control of libration angles and rates) until about 2 km below the Space Station. The TOMV will then accomplish the final maneuvers back to the station. The tether system operator will be responsible for reeling in slack tether without applying tension to the TOMV.

Using the Space Station RMS, grasp the OTV, disengage the OMV docking mechanism and stow the OTV. The OMV will then dock to its berthing location on the Space Station.

Using EVA, remove the tether sling from the OMV and restow.

1. USING EVA, INSTALL THE SUPPORT SLING ON THE OMV AND ATTACH IT TO THE TETHER.
2. DISENGAGE THE TOMV DOCKING LATCHES AND INITIATE TETHER DEPLOYMENT BY MANEUVERING THE TOMV AWAY FROM THE STATION WITH THE SLACK TETHER TRAILING BEHIND.
3. AT 1-2 KM BELOW THE SPACE STATION DISCONTINUE ACTIVE THRUSTING FOR TETHER TENSIONING AND CONTINUE DEPLOYMENT WITH GRAVITY GRADIENT FORCES.
4. AT SPECIFIED DEPLOYMENT LENGTH STOP DEPLOYING AND STABILIZE.
5. TRANSFER TO AUTOMATIC RENDEZVOUS MODE (OMV THRUSTING AND TETHER REELING CONTROLLED BY COMPUTER) AT APPROPRIATE TIME (TBD MIN.) BEFORE OTV INTERCEPT, UNTIL FINAL DOCKING IS COMPLETE.
6. THE OTV WILL MAINTAIN ATTITUDE HOLD UNTIL CAPTURE HAS BEEN ACCOMPLISHED. AT THAT TIME ATTITUDE CONTROL WILL BE ASSUMED BY THE TOMV.
7. STABILIZE TETHER AFTER DOCKING WITH TOMV THRUSTERS AND INITIATE RETRIEVAL SEQUENCE.
8. CONTINUE RETRIEVAL (WITH ACTIVE TOMV CONTROL OF LIBRATION ANGLES AND RATES) UNTIL ABOUT 2 KM BELOW THE SPACE STATION.
9. USE THE TOMV TO ACCOMPLISH THE FINAL MANEUVERS (REELING IN SLACK TETHER).
10. USING THE SPACE STATION RMS, GRASP THE OTV, DISENGAGE THE OMV DOCKING MECHANISM AND STOW THE OTV.
11. THE OMV WILL DOCK TO ITS BERTHING LOCATION ON THE SPACE STATION.
12. USING EVA, REMOVE THE TETHER SLING FROM THE OMV AND RESTOW.

Tethered OMV Rendezvous with Returning OTV

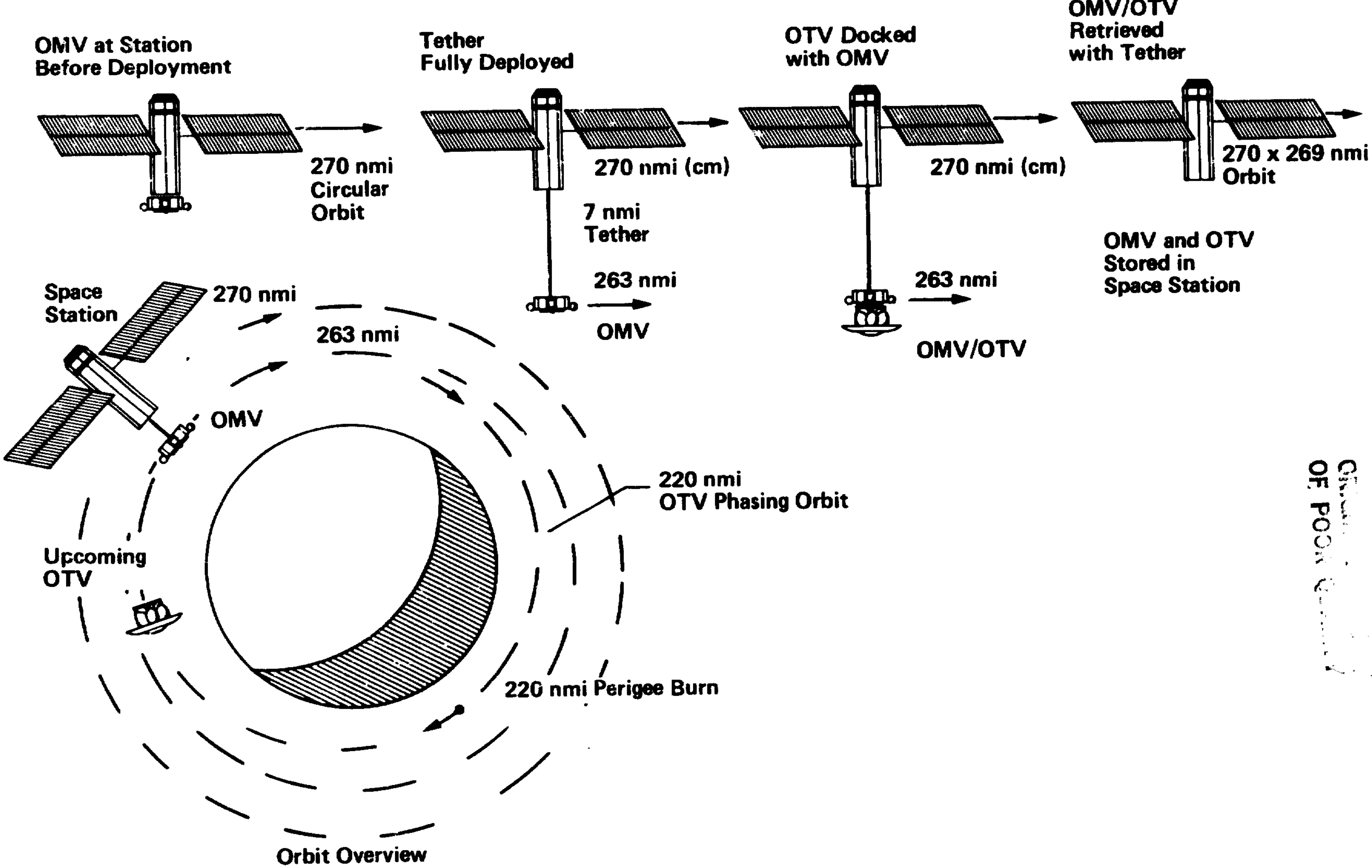
The Space Station with the TOMV is initially in a 270 nmi (500 km) circular orbit at an orbit inclination of 28.5 degrees before tether deployment. The OTV will return from its mission via aerobraking in the upper atmosphere and attain a 220 nmi (407 km) circular phasing orbit. A tether length of 7 nmi (13 km) is necessary to achieve matching velocity conditions between the TOMV and the OTV at the apogee of the OTV transfer orbit.

Since the 6.3 klb (2858 kg) mass of the TOMV is small compared to the 300 klb (136,100 kg) mass of the Space Station, upward movement of the station is very small as the TOMV is deployed down to its altitude of 263 nmi (487 km).

After tether stabilization and OTV orbit phasing is complete the OTV is placed on a Hohmann transfer ellipse to intercept the OMV at apogee. Mid-course OTV maneuvers will be utilized during this period.

After final rendezvous and docking, the tethered mass has increased to 12.3 klb (5,580 kg). Again, Space Station altitude change is very small, and the previous orbits are maintained. Retrieving the OMV/OTV stack slightly changes the Space Station orbit from circular to a 269 nmi (498 km) by 270 nmi (500 km) elliptical orbit.

Tethered OMV Rendezvous with Returning OTV



Relative Motion of OTV with OMV Near Rendezvous (-1.0 Min to +1.0 Min)

The accompanying chart shows the relative motion (position and velocity) of the OTV in the TOMV moving reference frame. The motion is based on an OTV apogee intercept for exact rendezvous conditions. The actual altitude at zero time is 263 nmi (487 km) with the OTV having originated from a 220 nmi (407 km) by 263 nmi (487 km) transfer orbit.

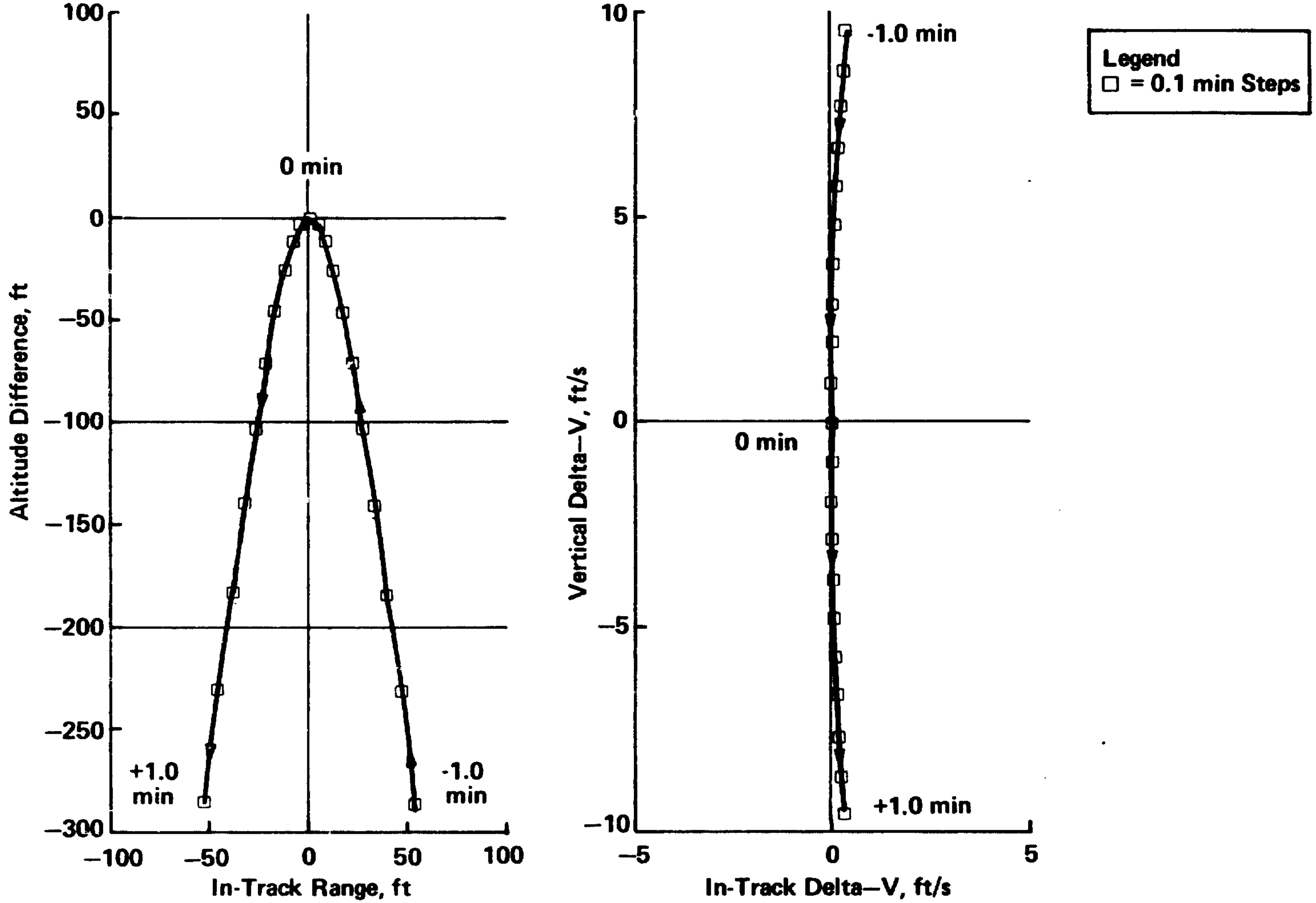
This is a unique type of rendezvous in the sense that the relative velocity between the TOMV and OTV is automatically zero at intercept, if exact conditions are met.

The plots shown how rapidly the relative position and velocity changes from one minute before intercept (-1.0 Min) to one minute after intercept (+1.0 Min). Primary motion is in the vertical direction (change in altitude) with altitude changing about 285 ft. in 1 Min. while in-track distance changes only 55 ft. in the same period. Relative velocity changes from about 9.5 ft/sec to zero in 1 Min. (This corresponds to about 1 ft/sec in 6 sec at intercept).

It is believed that this type of rendezvous will require an automatic rendezvous technique. This technique would be implemented by cooperative control of tether reeling (altitude control) and TOMV thrusting for cross-track and in-track control.

GPS position and velocity is available to both the TOMV and OTV during the OTV transfer orbit and should enable the OTV to make sufficiently accurate mid-course correction maneuvers to enable the TOMV to achieve rendezvous and docking.

Relative Motion of OTV with OMV Near Rendezvous



Tether System Design Considerations

Due to the geometry of the oscillation point rendezvous between the TOMV and the OTV shown in the preceding chart D-4.2, the TOMV will be oriented with the capture interface toward nadir and the OTV will be oriented with the capture probe toward the zenith.

A three point sling suspension will be used to attach the TOMV to the tether. This suspension will attach to the TOMV trunnion pins and will encompass the center-of-mass of the TOMV such that it will hang in a horizontal orientation.

A guillotine device to sever the tether will be provided at the Space Station. There is a remaining area of concern with respect to the ability of the TOMV to return to the Space Station with the severed tether end still attached. If it is determined that this is not possible a requirement for pyrotechnic separation capability will be added to the sling attachment interface. This would be commanded from Space Station or ground thru the TOMV communication link.

The final adjustments of position for the rendezvous are to be accomplished by a use of the TOMV RCS thrusters to maneuver in the horizontal plane and by use of the tether reel for vertical adjustment. The time response for the vertical adjustments will depend on the response characteristics of the tether reel system. Improvement in this response characteristic may be accomplished by use of tether aligned TOMV thrusters.

Because of the precision required for the final rendezvous, an automated computer control of these maneuvers will be required. Initial inputs to the system will be derived from GPS data for the two vehicles and final closing will be from television imagery from the TOMV.

- THE TOMV WILL BE ORIENTED WITH ITS CAPTURE/DOCKING INTERFACE TOWARD NADIR
- USE A 3 POINT SUPPORT SLING TO ATTACH THE TETHER TO THE OMV. ATTACH TO THE OMV TRUNNION PINS WITH QUICK DISCONNECT. ATTACH DEVICES SUITABLE FOR EVA INSTALLATION.
- A SECTION OF THE TETHER SLING NEAREST THE TOMV IS TO BE CONSTRUCTED OF HIGH TEMPERATURE RATED MATERIAL (E.G., STAINLESS STEEL) FOR COMPATIBILITY WITH TOMV THRUSTER OPERATION.
- TORQUE INPUTS TO THE STATION DUE TO TETHER TENSION FORCE ARE TO BE MINIMIZED BY USE OF A TENSION ALIGNMENT MECHANISM.
- BRAKING ENERGY GENERATED DURING DEPLOYMENT OF THE TOMV WILL BE ACCOMMODATED BY THE STATION THERMAL CONTROL BUS.
- SPACE STATION POWER WILL BE UTILIZED FOR RETRIEVAL OF THE TOMV AND OTV STACK.
- EMERGENCY RELEASE OF THE TETHER BY GUILLOTINE TO BE PROVIDED AT THE SPACE STATION END ONLY.
- RF COMMUNICATION DATA/COMMAND LINKS BETWEEN THE STATION AND THE OMV AND BETWEEN STATION AND OTV ARE REQUIRED.
- INITIAL DEPLOYMENT OF THE TOMV AND FINAL CLOSE-IN RETRIEVAL OPERATIONS WILL BE EFFECTED BY THE TOMV. TRANSITION TO GRAVITY GRADIENT FORCES AT 1 TO 2 KM SEPARATION.
- TENSION FORCES
  - STATIC TENSION FOR TOMV AT 7 NMI (13 KM): 30 LBF (134N)
  - STATIC TENSION FOR TOMV AND OTV: 58 LBF (257N)
  - ALLOWING FOR RESERVE TETHER LENGTH AND POSSIBLE DYNAMIC EFFECTS USE A DESIGN TENSION CRITERIA OF 150 LBF (668N)
  - DESIGN FACTOR: 2.5 OR BETTER

MARTIN MARIETTA

Tether Dynamics

The process of deploying the tethered orbital maneuvering vehicle and of retrieving the combined orbital maneuvering and orbital transfer vehicles is considered to be a straightforward process analogus to other operations which have been analyzed in detail. It has been assumed for this analysis that these operations will present no unusual problems.

The remaining areas of concern for this concept are the tether dynamics associated with the proposed implementation of the rendezvous maneuvers and then, subsequent to capture of the OTV, the attenuation of residual velocities and angular rates between the two vehicles.

The rendezvous maneuvering method adopted for this study utilizes the OMV RCS thrusters for maneuvers in the horizontal plane perpendicular to the tether and actuation of the tether reel for vertical adjustments parallel to the tether. Tether aligned thrusters on the OMV may also be used to improve the time response characteristics for vertical adjustments in position. These maneuvers are to be controlled by an automated rendezvous control system which utilizes GPS derived location inputs for the two rendezvous vehicles. The system will also use imagery of the approaching OTV derived from the OMV teleoperator system.

Precise characterization of the tether dynamics and time constants will be required to verify feasibility of this system concept.

- DEPLOYMENT OF THE TETHERED OMV AND RETRIEVAL OF COMBINED TOMV AND OTV ARE ANOLOGUS TO OTHER PLANNED TETHER OPERATIONS.
- NO UNUSUAL PROBLEMS ANTICIPATED WITH THESE OPERATIONS.
- TETHER DYNAMICS INDUCED BY THE RENDEZVOUS MANEUVERS AND CAPTURE REQUIRE FURTHER STUDY.
- TETHER RESPONSE TIME CHARACTERISTICS AND DYNAMIC RESPONSE ARE IMPORTANT ELEMENTS IN THE RENDEZVOUS MANEUVER CONCEPT USED.
- RENDEZVOUS TO BE ACCOMPLISHED BY COMPUTER CONTROL OF THE TOMV RCS THRUSTERS AND THE TETHER REEL DRIVE USED IN CONCERT.
- THERE WILL ALSO BE A MONITORING AND MANUAL OVERRIDE CAPABILITY AVAILABLE TO THE TETHER SYSTEM OPERATOR. THE OPERATOR WILL HAVE ACCESS TO THE GPS DERIVED LOCATION DATA AND TO TELEOPERATOR VIDEO DATA FROM THE TOMV.

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Functional Requirements

The functional requirements allocations to the OTV and the TOMV are listed in the facing chart.

The tether attachment sling provides the interface between the TOMV and the tether.

The tether characteristics required are listed.

Kevlar 49 was selected to minimize the amount of stretch in the tether in order to improve the reel-in/reel-out response time.

- ORBITAL TRANSFER VEHICLE (OTV)
  - VERTICAL MODE ATTITUDE HOLD CAPABILITY
  - GPS RECEIVER
  - RF COMMUNICATIONS LINK TO SPACE STATION
  - OMV COMPATIBLE CAPTURE PROBE
  - OMV COMPATIBLE DOCKING INTERFACE
- TETHERED ORBITAL MANEUVERING VEHICLE (TOMV)
  - ATTACHMENT INTERFACE FOR TETHER SLING
  - PREHENSILE CAPTURE AND ATTENUATOR MECHANISM
  - GPS RECEIVER
  - RF COMMUNICATIONS LINK TO SPACE STATION
- TETHER ATTACHMENT SLING
  - PROVIDES 3 POINT ATTACHMENT TO TOMV AT TRUNNION PINS
  - ATTACHES TO TETHER END
- TETHER
  - DEPLOYED LENGTH: 7 NMI (13 KM), PLUS REEL RESERVE: 3 NMI (5.5 KM)
  - MAXIMUM TENSION: 150 LBF (668N)
  - DESIGN FACTOR: 2.5 OR BETTER
  - MULTIPLE REUSE (20X)
  - SELECTED TETHER
    KEVLAR 49 BRAID
    KEVLAR DIAMETER: 0.065 IN (1.65 MM)
    TEFLON JACKETED DIAMETER: 0.085 IN (2.16 MM)
    MASS/LENGTH: 1.8 LBM/KFT (2.7 KG/KM)
    DEPLOYED TETHER MASS: 77 LBM (35 KG)

(CONTINUED)

Functional Requirements (Continued)

The tether alignment mechanism is required to minimize torques on the station from the tension force. it will be controlled by the station attitude control system and will require an operational interface with the station control system.

The device must provided stowage capabilities for the tether sling when it is detached from the TOMV. Use of the station RMS and EVA will be required to attach and detach the sling to the TOMV at its berthing location.

The tether reel and drive are to be sized to accommodate the required amount of tether shown. The major unique aspect of this reel/drive system is that it is to be aucomatically controlled by the rendezvous adjust system and the drive capacity must be designed in accord with the reel rate requirements of this system.

- TENSION ALIGNMENT MECHANISM
  - PROVIDE CAPABILITY TO ALIGN TENSION VECTOR TO STATION CM
  - RANGE OF TETHER ANGLES WITHIN A 10° HALF ANGLE CONE
  - CONTROLLED BY SPACE STATION ATTITUDE CONTROL SYSTEM
  - PROVIDE STOWAGE INTERFACE/ATTACHMENTS FOR TETHER SLING
- TETHER REEL AND DRIVE
  - SIZED AND HOLD 10 NMI (18.5 KM) OF SELECTED TETHER
  - CONTROL INTERFACE WITH AUTOMATED RENDEZVOUS SYSTEM
  - REEL DRIVE TO PROVIDE DRIVE RATES IN ACCORD WITH RENDEZVOUS AND CAPTURE ALGORITHMS (TBD)
  - UTILIZE POWER FROM SPACE STATION BUS

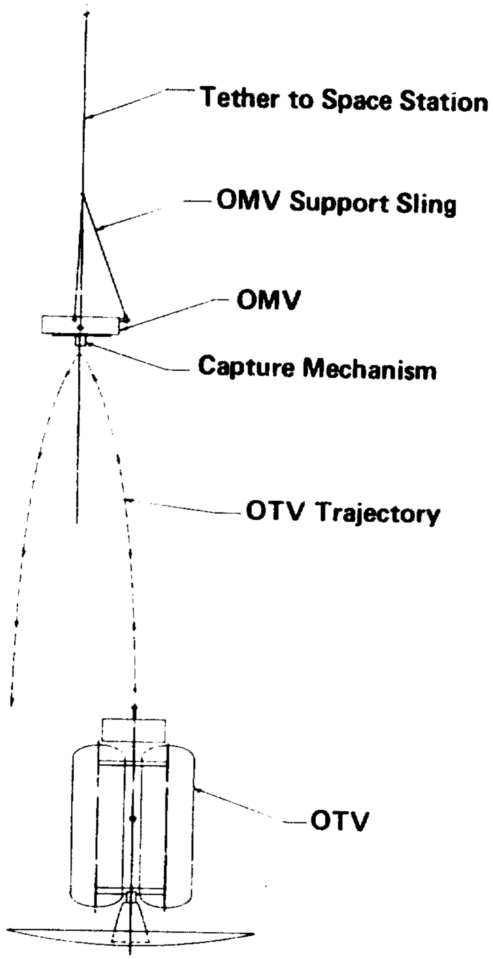
Tether Mediated Rendezvous

This viewgraph describes the relative attitude, position and approach trajectory of the Orbital Transfer Vehicle (OTV) and Orbital Maneuvering Vehicle (OMV) just prior to capture.

The OMV is deployed by tether from Space Station with its payload interface ring pointing toward NADIR. The three member support sling on the end of the tether stabilizes the OMV in the proper attitude.

The OMV deployment is controlled by the tether deployment reel to match the OTV trajectory. OMV and OTV attitude control systems are active during this time to insure proper intercept conditions. At final intercept the OMV capture mechanism closes on the OTV probe for initial capture. OMV latches will then be activated to rigidize the two vehicles for retrieval to Space Station.

Tether Mediated Rendezvous



Tether Mediated Rendezvous

Safety Considerations

No safety hazards have been identified for this concept.

- NO SAFETY HAZARDS HAVE BEEN IDENTIFIED FOR THIS CONCEPT.

Areas Needing Further Study

Determine the range over which the actual rendezvous contact between the free flying OTV and the tethered OMV can be adjusted by maneuvering the OMV in the horizontal plane and by adjusting the tether length through reel action. These actions have different time constants which must be considered in the design of an operational system.

The determination of the range of adjustment achievable will result in the definition of a target "box" for the rendezvous. This in turn will define the accuracy and precision requirements for setting up the planned rendezvous.

Because of the precise timing requirements for achieving the capture of the target OTV, an automated system for making the final rendezvous maneuvers is required to insure success. These systems are under study for more conventional rendezvous operations. This type of rendezvous should be added for consideration.

The final capture region can be significantly enlarged by the development of a prehensile mechanism which can extent outward from its location on the TOMV and grasp the capture probe on the OTV. The mechanism must be capable of attenuating any residual relative velocity and angular rates between the vehicles and then effecting a hard dock connection between them.

After the jointed TOMV and OTV have been retrieved to the station vicinity, the OTV will be activated to carry out the final stage of OTV delivery to the station. This process is similar to its planned/normal mode of operation with the exception of the presence of the slack tether still attached. This mode should be examined to insure feasibility.

AREAS NEEDING FURTHER STUDY

- o RANGE OF ADJUSTMENT OF RENDEZVOUS POINT ACHIEVABLE.
- o CONSTRAINTS ON KNOWLEDGE/CONTROL OF ORBIT PARAMETERS TO ACHIEVE RENDEZVOUS.
- o AUTOMATED RENDEZVOUS CONTROL SYSTEMS.
- o CAPTURE/ATTENUATION MECHANISMS.
- o STATION PROXIMITY RETRIEVAL OPERATIONS.

MARTIN MARIETTA

Technology Development

Automated rendezvous and capture guidance systems are currently under study as a method of carrying out these operations between free flying vehicles. These operations are an important element of projected operating modes for the Space Station and STS systems. The tethered OMV rendezvous is even more critically dependent on automated precision and timing because of the precision required for both location and timing.

As with the automated guidance above, there is a general need for prehensile capture devices to enlarge the envelope for successful capture and to attenuate residual velocities and angular rate. Development of such capture devices will benefit a variety of capture techniques.

Any serious consideration of this technique would require extensive simulation testing to establish success probability over a range of conditions. Existing and planned simulations should be easily adapted to accommodate these tests.

- AUTOMATED RENDEZVOUS/CAPTURE GUIDANCE SYSTEMS.
- PREHENSILE CAPTURE/ATTENUATION MECHANISMS.
- SIMULATOR OPERATIONS TO ESTABLISH VALIDITY OF RENDEZVOUS/CAPTURE PROCESS.

Conventional OMV Retrieval of OTV From Space Station

As currently envisioned, the returning OTV is placed in a phasing orbit (e.g., 220 nmi or 407 km) after aerobraking maneuvers are complete. After an appropriate phasing interval the OTV will transfer to an orbit within about 10 nmi (18.5 km) of the Space Station (e.g., 260 nmi, or 481 km) to await the arrival of the OMV.

The OMV will separate from the Space Station and transfer to the 260 nmi (481 km) orbit for rendezvous and docking with the OTV. After sufficient orbit phasing (in the 260 nmi orbit or an intermediate phasing orbit), the OMV/OTV stack is transferred to the Space Station orbit.

The OMV then accomplishes final rendezvous with the Space Station. The Space Station RMS will then grasp the OTV, disengage the docking mechanism and stow the OTV. The OMV will dock to the berthing location.

CONVENTIONAL OMV RETRIEVAL OF OTV FROM SPACE STATION

- o RETURNING OTV IS PLACED IN PHASING ORBIT (E.G., 220 NMI) AFTER AERO-BRAKING MANEUVERS ARE COMPLETE.
- o AFTER APPROPRIATE TIME OTV TRANSFERS TO AN ORBIT WITHIN 10 NMI OF THE SPACE STATION ORBIT (E.G., 260 NMI) TO AWAIT THE ARRIVAL OF THE OMV.
- o OMV SEPARATES FROM SPACE STATION AND TRANSFERS TO 260 NMI ORBIT FOR RENDEZVOUS WITH OTV. OMV DOCKS WITH OTV.
- o AFTER SUFFICIENT PHASING (IN 260 NMI ORBIT OR INTERMEDIATE PHASING ORBIT), OMV/OTV STACK TRANSFERS TO VICINITY OF SPACE STATION.
- o OMS DOES FINAL RENDEZVOUS WITH SPACE STATION.
- o RMS STOWS OTV AND OMV DOCKS TO ITS BERTHING LOCATION.

MARTIN MARIETTA

1. TETHER MEDIATED RENDEZVOUS OF AN OMV WITH A RETURNING OTV AND RETRIEVAL BY TETHER APPEARS TO BE FEASIBLE.
2. TETHERED OMV OPERATIONS WILL PROVIDE SIGNIFICANT PROPELLANT SAVINGS OVER COMPARABLE FREE-FLYING OMV MODE. OTV PROPELLANT REQUIREMENTS ARE ALSO REDUCED.
3. NO OMV MODIFICATIONS ARE REQUIRED AFFECTING PERFORMANCE IN THE NORMAL FREE-FLYING MODE.
4. CONTINGENCY RECOVERY MODES FOR THE OTV ARE AVAILABLE IN EVENT OF A MISSED OR ABORTED RENDEZVOUS. ALSO FOR THE OMV/OTV STACK IN EVENT OF AN ABORTED RETRIEVAL.
5. TETHERED RENDEZVOUS OPERATIONS OF THIS ORDER HAVE NEGLIGIBLE EFFECTS ON SPACE STATION ORBIT.

MARTIN MARIETTA

1. CONTINUE STUDY OF THE TETHERED OMV RENDEZVOUS AND DOCKING TO CONFIRM FEASIBILITY AND DEVELOP OPERATIONAL TECHNIQUES.
2. EXPAND SCOPE TO CONSIDER OTHER CANDIDATE MISSIONS AND BENEFITS OF TETHERED OMV OPERATIONS ON THE SPACE STATION.

SECTION E

AN ELECTRODYNAMIC TETHER USED IN A DUAL MOTOR/GENERATOR MODE TO SERVE AS THE PRIMARY ENERGY STORAGE FACILITY FOR SPACE STATION.

MARTIN MARIETTA

Concept Definition

A conductive tether deployed from the Space Station will be used in an electrodynamic mode to convert orbital energy into electrical power and vice versa. This method will serve as the primary method for storing solar energy for use during the eclipse portion of the orbit.

The system will function in a balanced mode such that the amount of orbital-energy converted to electrical power during the eclipse is balanced by an equivalent amount restored during the sunlit portion of the orbit.

During the eclipse the electromotive potential induced in the tether by the motion across the earths magnetic field is used to drive a current through the tether. Power is extracted from this current to supply the station bus. The closure path for the current is by means of plasma contactors at the tether ends which provide low impedance contacts to the ionosphere plasma.

After the station has passed back into the sunlight the power from a solar conversion system will pick up the station power load and at the same time be used to drive a current thru the tether in the reverse direction. This will result in a thrust force on the system that will act to restore the orbital energy extracted during the eclipse pass.

- CONSISTS OF A CONDUCTIVE TETHER DEPLOYED FROM SPACE STATION TO SERVE AS PRIMARY ENERGY STORAGE METHOD.
- EQUIPPED WITH PLASMA CONTACTORS TO COMPLETE LOW IMPEDANCE CIRCUIT PATH THRU IONOSPHERE.
- DC/DC CONVERSION CIRCUITS TO ADAPT HIGH VOLTAGE TETHER CURRENTS TO SPACE STATION BUS.
- ALTERNATES BETWEEN GENERATOR (DRAG) MODE DURING ORBIT ECLIPSE PORTION AND MOTOR (THRUST) MODE DURING SUNLIT PORTION.
- GENERATOR MODE USED TO CONVERT ORBIT ENERGY TO ELECTRIC POWER TO SUPPLY STATION BUS.
- MOTOR MODE USED TO CONVERT SOLAR DERIVED ELECTRICAL POWER INTO THRUST WHICH IN TURN RESTORES ORBITAL ENERGY EXTRACTED EARLIER.

Ground Rules and Assumptions

The following ground rules were used:

1. The electrodynamic tether system is the primary energy storage method for the Space Station, and is to be sized to provide the full bus power of 120 kw.

2. Conventional back-up storage systems will be available for station operation during tether servicing or contingency modes.

3. No aerodynamic drag make-up provisions are included.

The following assumptions were made:

1. The ionosphere will provide a low impedance (1 ohm) current closure path at all times with no constraint on current levels.

2. Plasma contactors are available and will function as low impedance contacts between the tether ends and the ionosphere plasma.

3. There are no untoward effects on the functioning of photo-voltaic solar arrays due to the plasma contactor.

4. Current modulation in the tether can be used as a method to damp out tether oscillations.

GROUND RULES

- ED TETHER SYSTEM IS THE PRIMARY ENERGY STORAGE METHOD FOR SPACE STATION.
- SIZED TO PROVIDE 120 KW.
- CONVENTIONAL BACK-UP SYSTEM AVAILABLE FOR CONTINGENCIES.
- NO AERO DRAG MAKE-UP PROVISION.

ASSUMPTIONS

- LOW IMPEDANCE CURRENT PATH THRU IONOSPHERE.
- NO CONSTRAINTS ON CURRENT LEVEL.
- LOW IMPEDANCE PLASMA CONTACTORS ARE AVAILABLE.
- NO UNTOWARD EFFECTS ON SOLAR ARRAYS.
- TETHER OSCILLATION DAMPING CAN BE EFFECTED BY CURRENT MODULATION.

Operations Concept

The operations sequence for the deployment of the tether and placing it into operation is given.

STATUS: STATION POWER SYSTEM OPERATING ON BACKUP ENERGY STORAGE SYSTEM. END EFFECTOR SATELLITE (EES) SERVICED AND READY TO DEPLOY.

DEPLOYMENT OPERATIONS

1. ACTIVATE STATION PLASMA CONTACTOR (PC) TO ANCHOR STATION POTENTIAL TO AMBIENT PLASMA POTENTIAL.
2. UNLATCH EES FROM SERVICING BERTH.
3. INITIATE DEPLOYMENT USING EES THRUSTERS AND CONTINUE TO GRAVITY GRADIENT TRANSITION POINT AT TBD METERS.
4. TERMINATE THRUSTER ACTION BY RF COMMAND LINK.
5. COMPLETE TETHER DEPLOYMENT TO FULL TETHER LENGTH USING GRAVITY GRADIENT TENSION FORCE.
6. ACTIVATE THE EES PC BY RF COMMAND LINK.
7. ACTIVATE THE DC/DC CONVERTER/POWER SUPPLY CIRCUIT. MODE WILL BE AUTOMATICALLY CONTROLLED BY POWER MANAGEMENT SYSTEM TO CORRESPOND TO THE LIGHTING PHASE OF THE ORBIT.
8. SWITCH BACKUP ENERGY STORAGE SYSTEM TO STANDBY.
9. CREW REVERTS TO NORMAL OPERATIONS.

Operations Concept (Continued)

The operations sequence for on-line operational periods and for retrieval of the tether for servicing and maintenance are shown.

ON-LINE OPERATIONS

- ON-LINE OPERATIONAL INTERVALS NOMINALLY 6 MONTHS DURATION. (PRIMARILY DETERMINED BY ARGON RESUPPLY REQUIREMENTS).
- DURING OPERATIONAL INTERVAL SYSTEM MANAGED BY AUTOMATED CONTROL.
  - ALTERNATION BETWEEN DRAG AND THRUST MODES
  - ADJUST DC/DC CONVERTER/POWER SUPPLY MODULES FOR VARIATIONS IN TETHER VOLTAGE
  - CONTROLS CURRENT MODULATION REQUIRED FOR TETHER DAMPING

RETRIEVAL FOR SERVICING

1. ACTIVATE BACKUP SYSTEM.
2. DEACTIVATE DC/DC CONVERTER/POWER SUPPLY.
3. DEACTIVATE EES PC USING RF COMMAND LINK.
4. INITIATE RETRIEVAL USING REEL AND RETRIEVE TO GRAVITY GRADIENT TRANSITION POINT AT (TBD) METERS.
5. ACTIVATE EES THRUSTER SYSTEM (RF COMMAND LINK).
6. COMPLETE RETRIEVAL, CAPTURE AND BERTH THE EES.
7. DEACTIVATE STATION PC.
8. PERFORM SERVICING OF EES (ARGON RESUPPLY, PROPELLANT LOADING, CHECKOUT).
9. REVERT TO DEPLOYMENT OPERATIONS SEQUENCE.

Orbit Considerations

The Space Station has been assumed to be in a nominal 270 nmi (500 km) circular orbit at 28.5 degree inclination.

Use a tether mass of 15,870 lbm (7199 kg), an end effector satellite mass of 2,317 lbm (1050 kg), and a tether length of 31 km.

The resulting tension in the tether is 115 lbf (514N).

The induced acceleration level on the station is 3.8×10^{-4}g.

Orbit perturbation effects due to the electrodynamic cross-track forces and to the alternating drag and thrust forces during each orbit have been considered of second order and have not been analyzed in this study.

- SPACE STATION 2 KM FROM SYSTEM CM.
- TETHER TENSION: 115 LBF (514N).
- ACCELERATION LEVEL ON STATION 3.8 X 10^{-4}G.
- SECONDARY ORBIT PERTURBATION EFFECTS NOT ANALYZED.

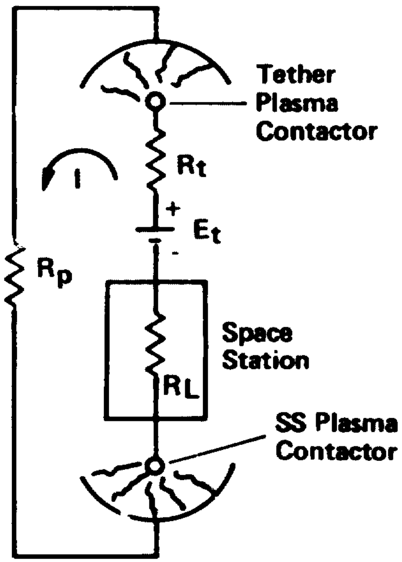
System Power Budget - Generator Mode

This chart lists the system power allocation budget used for system design consideration.

The allocations for the plasma contactors and for ionospheric heating are not well understood but they are probably of the correct order of magnitude and they are a relatively small fraction of the major allocation items.

The station drag effect for this level of power generated is 39 Newtons.

System Power Budget - Generator Mode



	kW
Bus Power	120.0
Station Plasma Contactor	2
HV dc/dc Converter (90% Efficiency)	14
Tether Plasma Contactor	2
Ionosphere Heating	10
Total Load Power	148
Tether Power (Impedance Matched)	148
Total System Power	296

Using the Relation $F_d = \frac{P}{V}$

Station Drag $F_p = 39$ N

Where F_d = Drag Force
P = System Power
V = Orbit Velocity

Tether Design Considerations - Generator Mode

Based on the system power determined from the preceding chart a plot of the relationship between current I and tether resistance R_T is shown for the power in the tether. The relationship used is:

P_T = Power in tether = I^2R_T, where R_T = tether resistance.

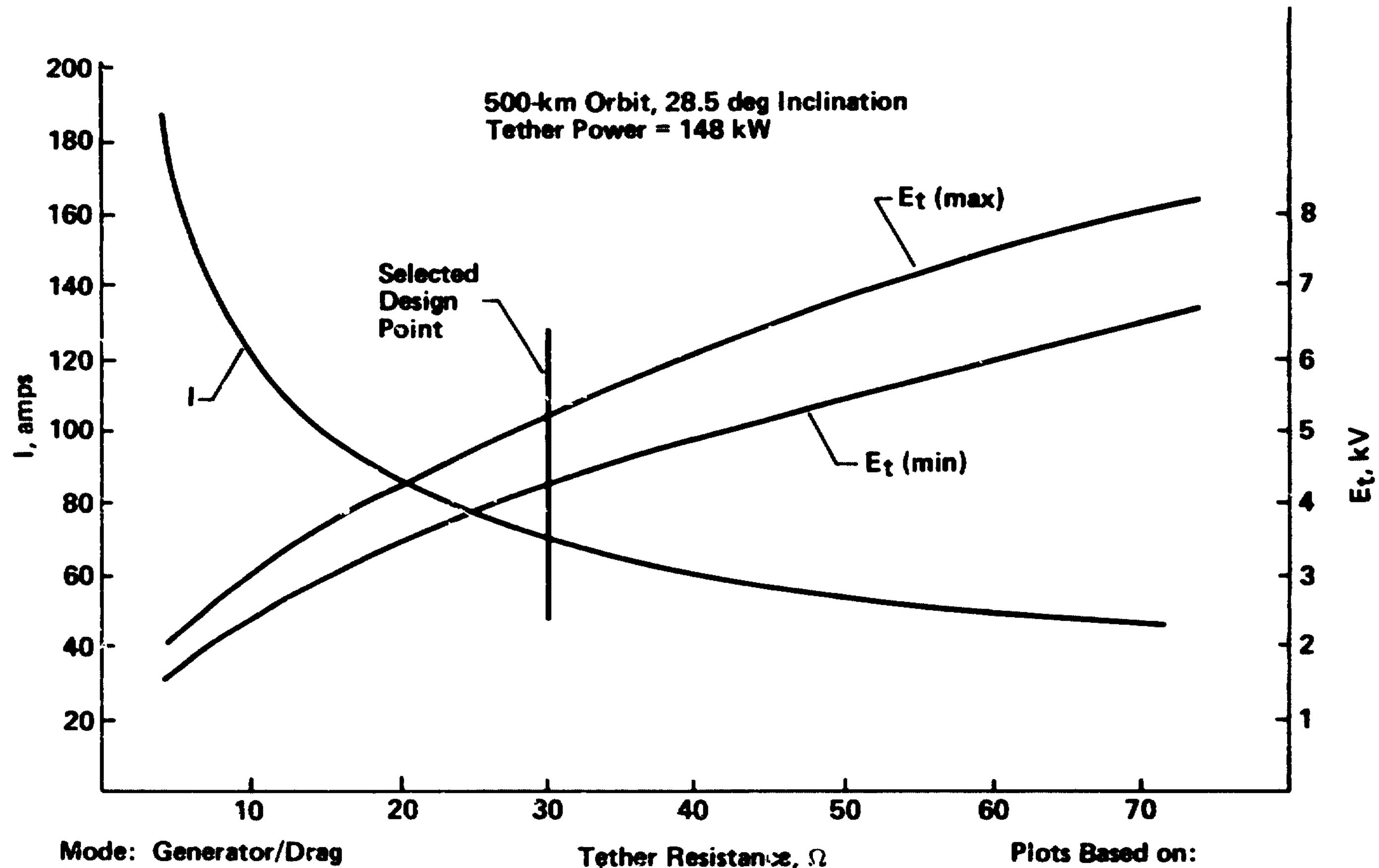
The minimum voltage required to drive this current thru the tether is calculated from the relationship.

$E_T \text{ (min)} = IR_T$

Based on the values of magnetic field strength at the 28.5 degree 270 nmi (500 km) orbit of the Space Station, the potential induced in a vertical tether is estimated at a minimum value of 136 volts per kilometer and a maximum of 169 volts per kilometer. Using this ratio of $\frac{169}{136}$ a curve for E_T (max) is plotted.

The selected design point for this concept analysis has been indicated by the vertical line.

Tether Design Considerations - Generator Mode



Mode: Generator/Drag

Power Levels:

Station Bus = 120 kW
Tether = 148 kW
System = 296 kW

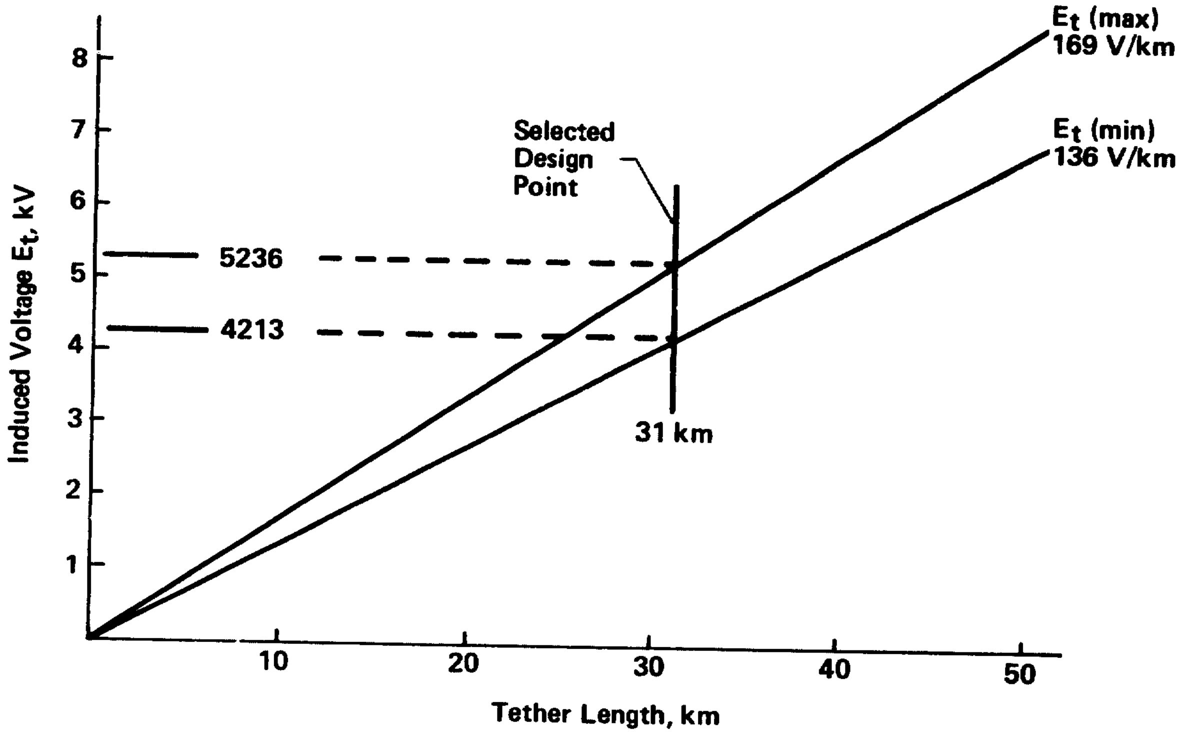
Plots Based on:

$P_t = I^2 R_t$
$E_t(\text{min}) = I R_t$
$E_t(\text{max}) = \frac{169}{136} E_t(\text{min})$

Tether Design Considerations

Using the values of E_T (min) and E_T (max) the relationship with tether length is plotted on the chart. The selected design point of 31 km for the tether is indicated by the vertical line.

Tether Design Considerations



Interval Time Considerations - Chart I

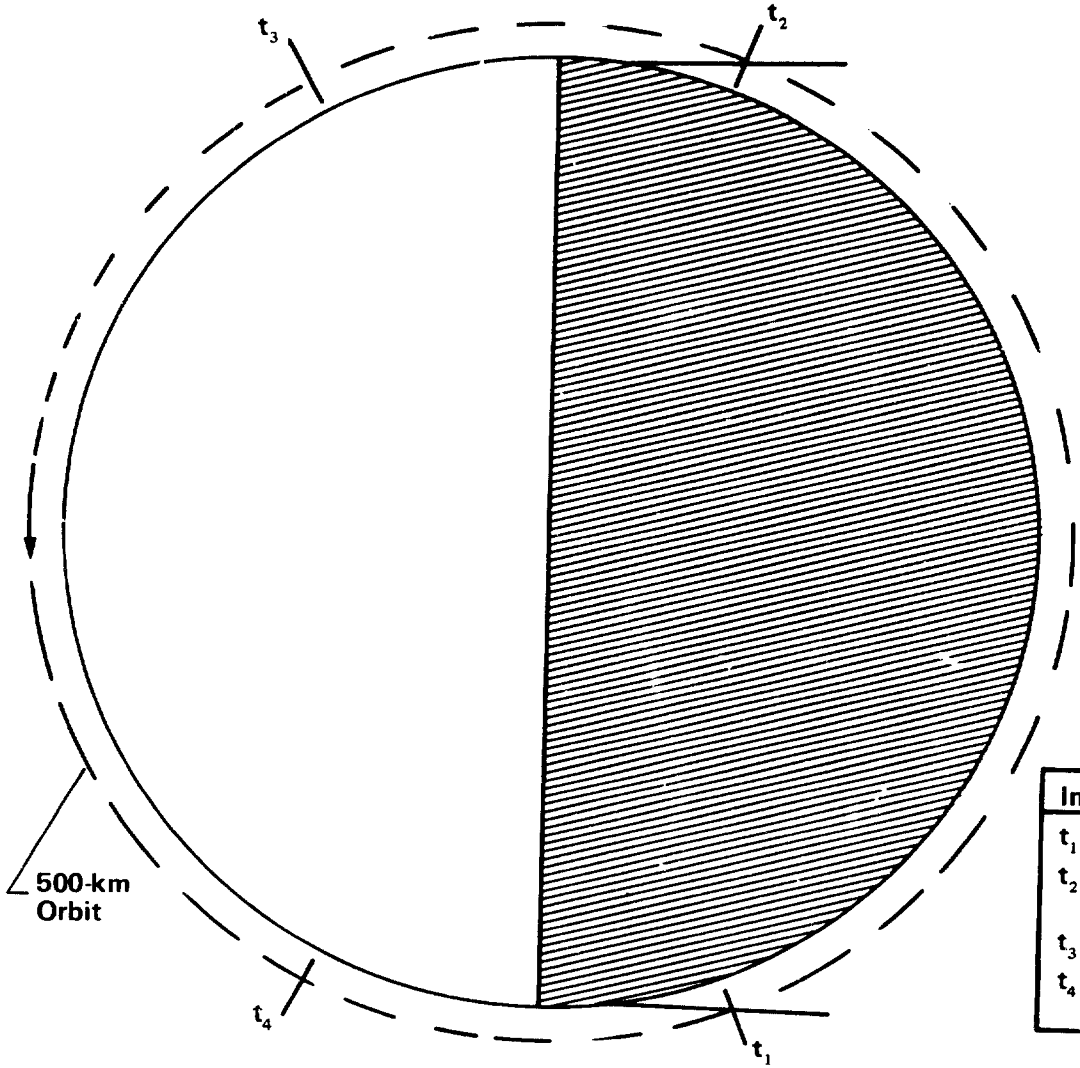
This chart shows the relationship between the eclipse interval designated as t_1 to t_2 when the tether is operating in the generator (drag) mode to provide power for the station, the transition interval from t_2 to t_3 when the mode is in process of being switched, the motor (thrust) mode from t_3 to t_4 when station power derived from solar arrays is being used to drive current thru the tether in opposition to its induced voltage and causing a thrust force on the station, and lastly a second transition interval from t_4 to t_1, when the mode is again being reversed.

The length of time required for the mode switching intervals is not well understood at this time and will require further analysis.

For purposes of this study the interval is conceived to be bounded by the natural period of the tether in-plane oscillation which has a period of 52 minutes or 26 minutes for a half cycle. If the current flow were reversed immediately on passage into the sunlight the transition interval could be shortened. Using an optimistic speculation that it could be reduced to half the natural interval gives an interval length of 13 minutes.

This estimated interval length will be used again in Charts 5.5 and 5.6.

Interval Time Considerations - I



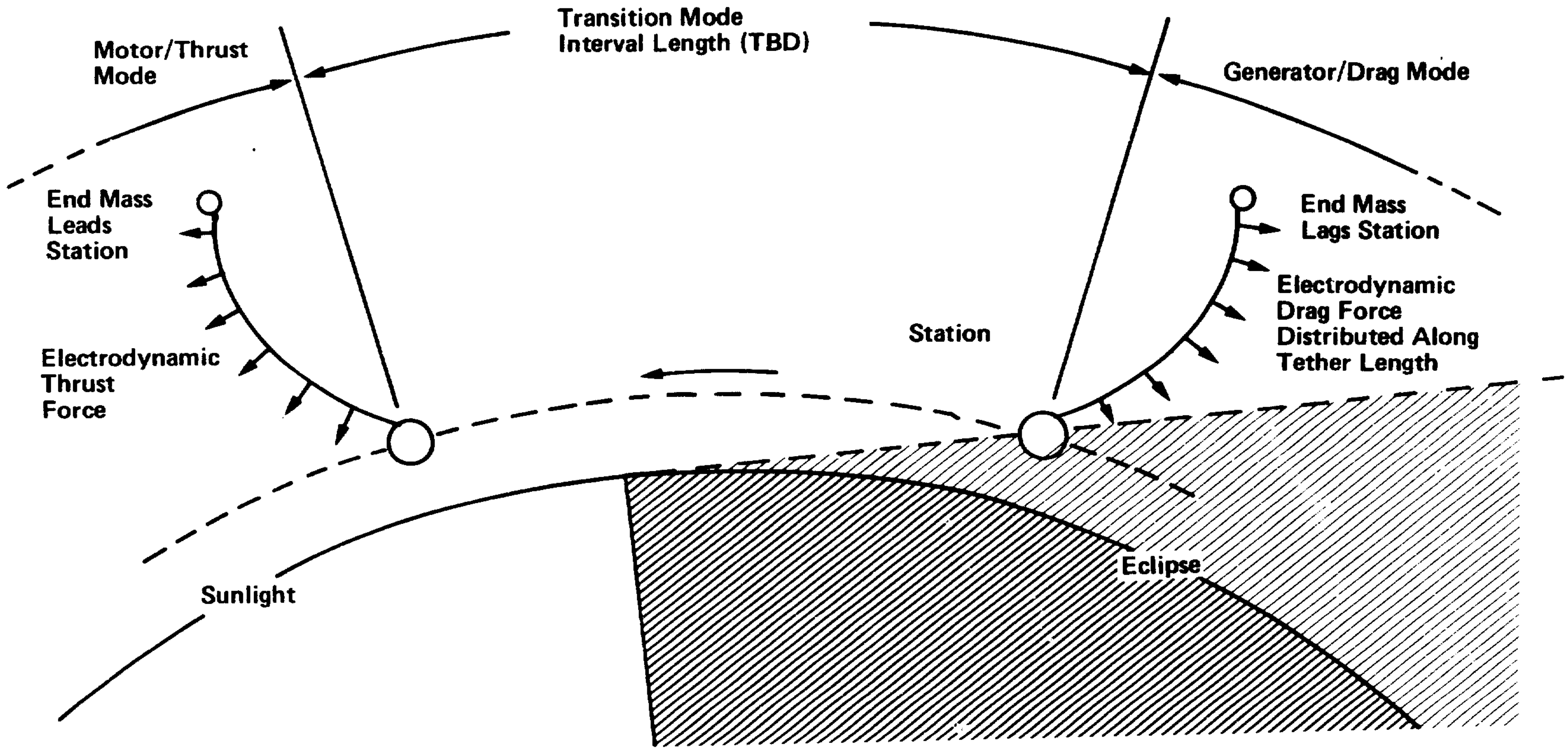
Interval	Lighting	Mode
t_1 to t_2	Eclipse	Generator/Drag
t_2 to t_3	Sun	Transition/ Drag to Thrust
t_3 to t_4	Sun	Motor/Thrust
t_4 to t_1	Sun	Transition/ Thrust to Drag

Mode Transition

This chart shows the nature of the required transition from the generator (drag) mode of operation on the right to the motor (thrust) mode shown on the left.

Between these two illustrated positions the tether and end mass must shift from a position lagging the station to one leading.

Mode Transition



Interval Time Considerations - Chart II

In order to maintain an equilibrium orbit altitude for the station the integrated drag force experienced in the eclipse portion of the orbit must be balanced by the integrated thrust force in the sunlit portion.

The plot shown is a conjectural interpretation of the drag and thrust forces around the orbit. Constant power and B values have been assumed for clarity. For this particular plot the optimistic 13 minute intervals for mode switching are used.

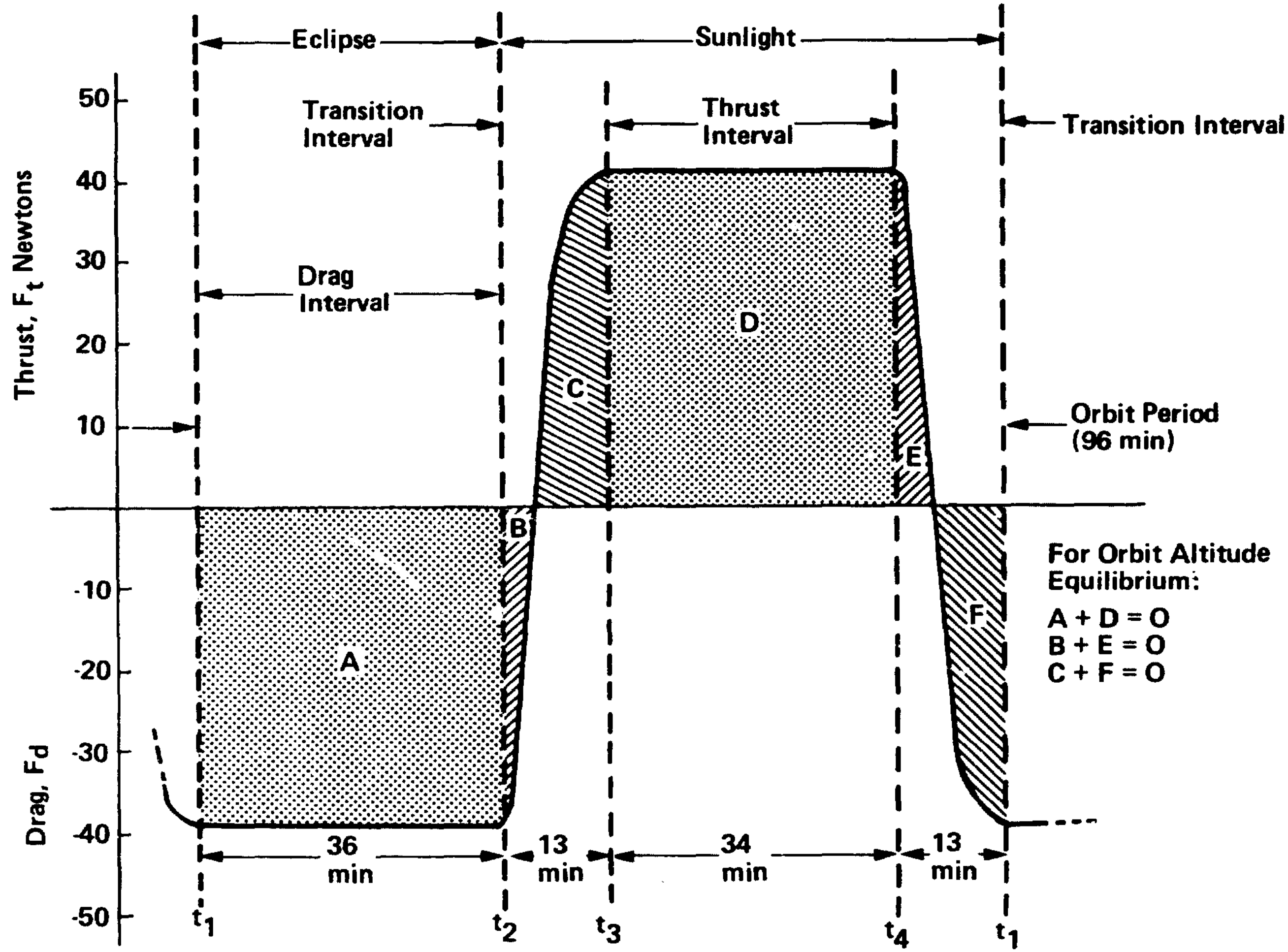
With an Orbit period of about 96 minutes and a maximum eclipse period of about 36 minutes (at beta angle equal to zero) it can be seen that the two intervals for mode switching leave a thrust integration period of 34 minutes. The two mode switching intervals will negate one another and make no net contribution to either drag or thrust.

Using these interval values we can determine the ratio of drag to thrust over the primary operating intervals t_1 to t_2 and t_3 to t_4.

This ratio is $$\frac{\text{drag}}{\text{thrust}} = \frac{36}{34}$$

This ratio is a key element in the sizing of the tether system for operation in the thrust mode.

Interval Time Considerations II



Refer to Preceding Chart for Definition of t_1, t_2, t_3, t_4

System Power Budget - Motor Mode

Using the ratio between drag and thrust as estimated from the preceding chart to calculate the required thrust force of 41.2 Newtons, and in turn the power in the tether required to produce this thrust we have a tether power requirement of 314 kW.

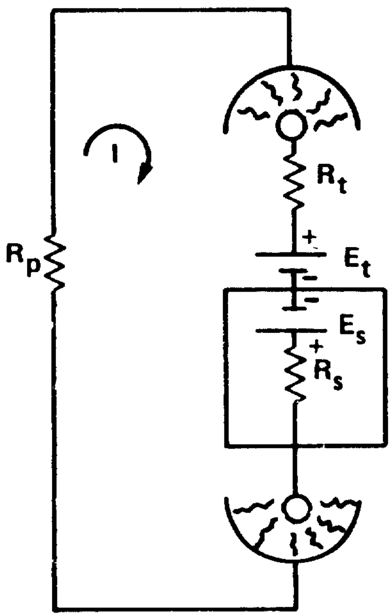
Again making a power budget allocation for the total system using the indicated schematic, a total system power requirement of 371 kW is determined.

This is the amount of processed solar array power that must be available to drive the tether during the t_3 to t_4 interval in order to maintain the station altitude at an equilibrium level.

This power must be supplied at a voltage adequate to drive the required current through the tether in opposition to the electrodynamically induced voltage. In the worst case this could be the E_T maximum voltage values identified earlier on Chart 5.3. This value of E_T maximum is 5236 volts for the selected 31 km tether.

System Power Budget - Motor Mode

System Schematic



E_s = HV Power Supply
E_t = Electrondynamic-Induced Voltage
R_p = Ionosphere Resistance
R_s = Source Resistance
R_t = Tether Resistance

Using an Assumed Ratio of Mode Intervals

$$\frac{\text{Drag}}{\text{Thrust}} = \frac{36}{34}\ ;\quad F_t = \frac{36}{34} F_d = 41.2\text{N}$$

Tether Power in Thrust Mode = F_tV = 314 kW

	kW
Tether Power	314
End Mass Plasma Contactor	2
Ionosphere Heating	15
Power Supply (90% Efficiency) (Applies to above Powers)	38
Plasma Contactor on Station	2
Total System Power	371

This is the Amount of Power That Must be Supplied by the Solar Array to the Tether System During the Thrust Mode Interval to Repay the Energy Extracted during the Drag Mode.

Note That the Voltage Supplied by the Station Power Supply Must Buck Out the Electrodynamic-Induced Voltage E_t.

Tether Design Considerations - Motor Mode

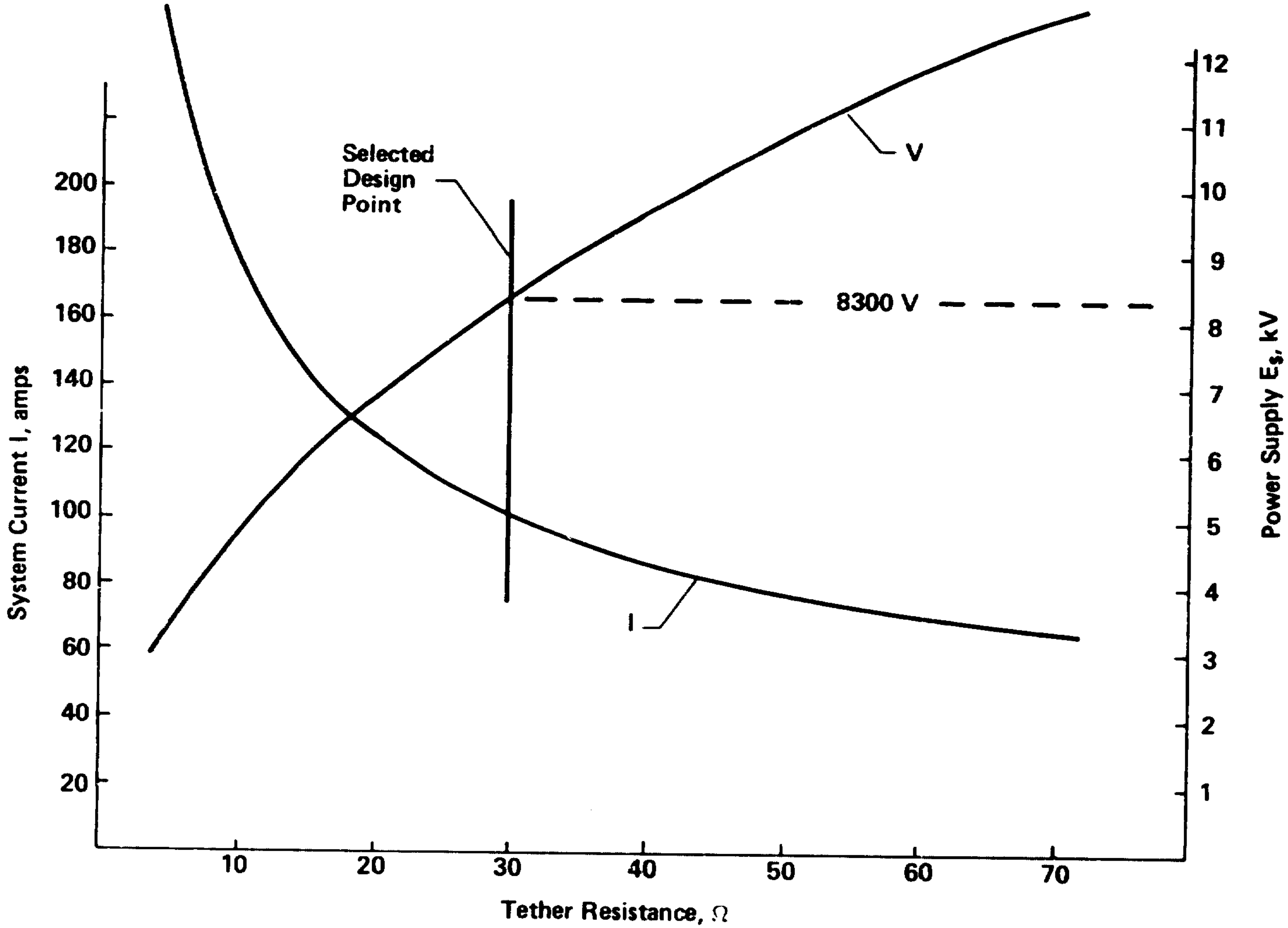
Again using the required tether power of 324 kW from chart 5.7 and the relationship $P_T = I^2R_T$, the curve of I versus R_T is plotted.

Using the relationship of IR_T calculate the voltage drop required to drive this current through the tether. This voltage must be applied over and in opposition to the electrodynamically induced voltage which is between E_T max and E_T min as shown on chart E-5.3.

The sum of E_T max and the voltage required to drive the current is plotted as the upper curve on this chart and shows the power supply voltage required to drive the tether.

Once again the selected design point for this study is shown by the vertical line. The indicated maximum voltage required from the power supply is 8300 volts at a current of approximately 100 amperes.

Tether Design Considerations - Motor Mode

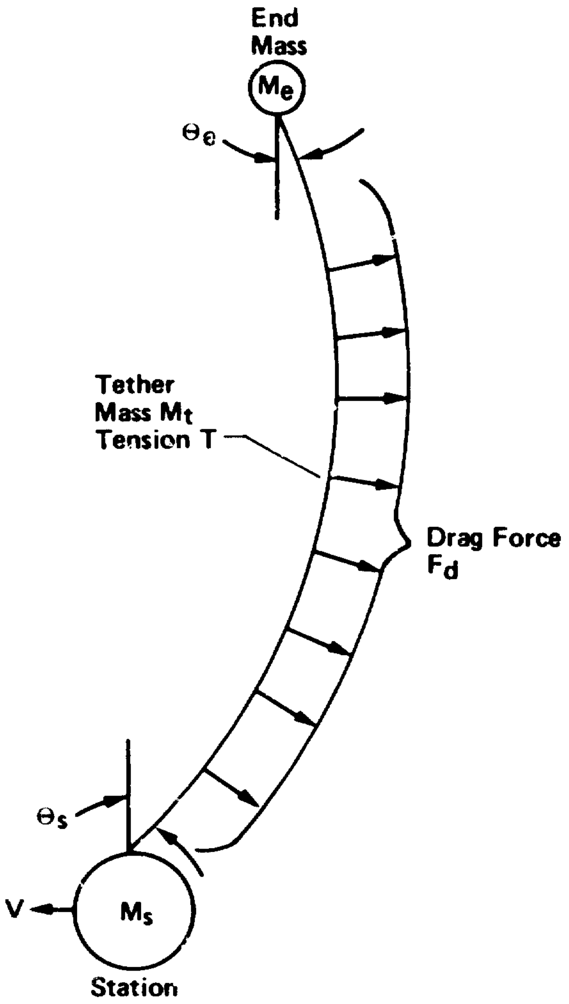


Tether Angle Relationships

This chart shows the relationships among the quantities for drag (F_D) (equally true for thrust, F_T), power level P, tether tension T, the station mass M_S, the end mass M_E, the tether mass M_T, and the angles to the vertical made by the tether at the station and end mass.

For this concept study we have selected an arbitrary limit on the tether angle to the station of 0.1 radian. For a given level of power this sets a constraint for the tether tension. The tension must be equal to or greater than this level to insure the tether angle does not exceed the constraint.

Tether Angle Relationships



Total Mass = M = $M_e + M_t + M_s$

In Equilibrium Condition
the Drag Force F_d Must Act on Each Element
in Proportion to its Fraction of Total Mass.

$F_d = F_e + F_t + F_s$

Using the Relation $F_d = \frac{P}{V}$

$$F_e = \frac{M_e}{M}\frac{P}{V}\ ;\ F_t = \frac{M_t}{M}\frac{P}{V}\ ;\ F_s = \frac{M_s}{M}\frac{P}{V}$$

Note That the Drag Forces on the
End Mass and Station are Applied
by the Horizontal Component of
the Tether Tension "T".

$F_e = T \text{ Sine } \Theta_e$ and $F_s = T \text{ Sine } \Theta_s$

$\Theta_e = \text{Sine}^{-1} \frac{F_e}{T}$ $\qquad \Theta_s = \text{Sine}^{-1} \frac{F_s}{T}$

Substituting for F_e and F_s, and Using
Small Angle Limits

$$\Theta_e = \frac{M_e}{M}\frac{P}{VT} \text{ or } \frac{M_e}{M}\frac{F_d}{T}$$

$$\Theta_s = \frac{M_s}{M}\frac{P}{VT} \text{ or } \frac{M_e}{M}\frac{F_d}{T}$$

Tether Tension Constraint

Using the relationship for tether tension, power level and angle derived on the preceding chart calculate the required tension constraint to keep the angle excursion below 0.1 radian.

The tension limit value is greater than or equal to 410 Newtons.

This value is used in selecting an appropriate tether size and material.

Tether Tension Constraint

Using the Relationship between Tether Angle and Tether Tension

$\Theta_s = \frac{M_s}{M} \frac{P}{VT}$ and Using a Constraint on $\Theta_s \leqslant 0.1$ rad

Tether Tension $T = \frac{M_s}{M} \frac{P}{V\Theta_s}$

$$\frac{M_s}{M} = \frac{M_s}{M_s + M_t + M_e} = \frac{300k}{300k + 17.5k + 1.5k} = \frac{300k}{319k} = 0.94$$

P = Maximum Power in Tether = 314kW

V = 7613M/s

$$T = 0.94 \times \frac{314000}{7613 \times 0.1} = 410N$$

Tether Tension $\geqslant$ 410 N to Ensure Tether Angle $\leqslant$ 0.1R

Tether Dynamics

Compared to non-conductive tethers, the dynamics of electrodynamic tethers are significantly more complicated. This is primarily due to the presence of distributed forces acting perpendicular to the tether and the significantly increased mass of the tether relative to the end masses. Simulation programs to study these dynamics are not generally available as yet.

Some of the specified areas of concern which have been identified in the course of this study are the following:

1. Deployment and retrieval operations - here the stiffness and mass of the tether require increased thrust levels from the end-effector for close-in deployment and retrieval operations.

2. Once the system is placed in operation, the electrical current in the tether will cause distributed forces perpendicular to the tether. These forces will have both in-plane and cross-track components. These varying perpendicular forces will result in shape profiles for the tether and the associated dynamics as these forces vary with time.

3. The cross-track component of the electrodynamic forces will induce cross-track oscillations of the tether. The variation in these forces is roughly at orbital frequency which is a subharmonic of the natural tether frequency for cross-track oscillations, which could result in resonant pumping of the oscillations. These forces are a function of the direction and magnitude of the tether current, the orbit beta angle (which determines the current switching position), and the relationship of the orbit to the magnetosphere.

4. The transition switching process from generator (drag) to motor (thrust) mode will cause a shift in the shape and position of the tether with associated transient effects.

5. Difficulties with using established dynamic control techniques to damp out oscillations have been identified for the electrodynamic tethers. The feasibility of using current modulation to perform the damping needs to be determined.

TETHER DYNAMICS

- o DYNAMICS OF ED TETHERS NOT WELL UNDERSTOOD
  - FORCES PERPENDICULAR TO TETHER
  - INCREASED TETHER MASS
  - MATURITY/AVAILABILITY OF SIMULATION PROGRAMS
- o SPECIFIC AREAS OF CONCERN
  - DEPLOY/RETRIEVE CLOSE-IN PHASES
  - TETHER SHAPE PROFILES/DYNAMICS
  - CROSS-TRACK OSCILLATION RESONANCE EFFECTS
  - TRANSITION FROM DRAG TO THRUST MODE
  - CURRENT MODULATION FOR OSCILLATION DAMPING

MARTIN MARIETTA

Functional Requirements

Tether End Mass Satellite

A hot gas propellant system was selected for the deploy and retrieve operations support because of the mass and stiffness of the conductive tether.

A retroreflector is required to permit tracking of the satellite location by the station radar system.

A Ku band transceiver link is required for sending commands and receiving housekeeping data. The transceiver will be supported by a fixed horn antenna.

A power converter system will be used to tap energy from the tether system to operate the satellite systems. This converter must accommodate the reversal of current flow in the tether as the system mode is alternated from drag to thrust and back again. Design concepts for this DC/DC converter have not been developed in this study.

A battery system will be required to support the satellite system during switching interval operations, for initialization and retrieval of the tether, and for contingency situations when the tether is not in electrodynamic operation.

A berthing interface with a stowage/servicing area on the station is required along with an RMS grapple fixture to provide handling capabilities for the satellite.

The satellite systems are to be designed for a cold biased passive thermal control concept.

Dual redundant plasma contactor devices are to be provided which are sized to provide the current levels indicated.

An argon gas supply system is to be provided to support the plasma contactor operator for a minimum of 6 month intervals.

A guillotine device to jettison the tether in event of a break may be required.

Tether

The tether is to be stranded copper wire equivalent to American Wire Gauge number 5.

It is to be insulated to 10 kV and temperature rated to 250°F (120°C).

It is to be coated with a thermal coating with absorbtivity/emissivity values of 0.15/0.85.

The length is 31 km and it will operate fully deployed with no remaining wraps on the reel. This is to avoid magnetic field effects and to avoid a temperature hot spot.

- TETHER END MASS SATELLITE
  - TETHER ALIGNED HOT GAS THRUSTER SYSTEM (DEPLOY AND RETRIEVE OPERATION ONLY)
  - PROPELLANT TANKAGE
  - RETROREFLECTOR(S) FOR LOCATION TRACKING BY STATION RADAR
  - KU BAND TRANSCEIVER WITH HORN ANTENNA
  - COMMAND DECODER/PROCESSOR
  - HOUSEKEEPING DATA PROCESSOR
  - TETHER TAP POWER CONVERSION SYSTEM TO POWER END MASS SYSTEMS
  - BATTERY POWER SYSTEM FOR TRANSITION INTERVALS AND EMERGENCIES
  - BERTHING INTERFACE FOR SERVICING ON STATION
  - RMS GRAPPLE FIXTURE
  - COLD BIASED PASSIVE THERMAL CONTROL
  - PLASMA CONTACTOR (S)
    GENERATOR MODE (END MASS POSITIVE) 70 AMPS
    MOTOR MODE (END MASS NEGATIVE) 105 AMPS
  - ARGON GAS SUPPLY SYSTEM (6 MONTH SERVICE INTERVAL)
  - TETHER GUILLOTINE
- TETHER
  - STRANDED COPPER EQUIVALENT TO AWG #5
  - INSULATED TO 10 KV
  - TEMPERATURE RATED TO 250^{o}F
  - THERMAL CONTROL COATED 0.15/C.85
  - LENGTH 31 KM
  - TETHER WILL OPERATE FULLY DEPLOYED

(CONT'D)

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Functional Requirements (Continued)

Tension Alignment Device

The alignment device is required to align the tension vector to the station center-of-mass for all conditions of build up, both with and without Shuttle present. In addition, the range of angle for the alternate modes of operation will vary between $\pm$ 6 degrees in plane. The amplitude of the cross plane libration angles are not well understood at this time but will probably be at least equal to the in-plane. It is conceivable that they could be significantly larger in amplitude. This is an area of concern that has been identified for further study.

The alignment device will be acting on the tether in a region where the full electrical potential exists between the tether conductor and the Space Station ground. This means adequate high voltage isolation must be incorporated into the design to accommodate a breakdown of the tether insulation.

The capability to berth and service the end mass satellite must be incorporated into the alignment mechanism design.

Tether Reel and Drive

The tether reel is to be sized to hold 31 km of the selected tether cable and to provide adequate power rating to perform the deploy and retrieve operations. The tether is designed to operate fully deployed, therefore, the reel drive is required to have the capability to drive to a full deployment and stop at that point. Libration damping by control law dynamics will not be usable for this concept because of problems with magnetic fields and heating associated with any residual wraps of tether on the reel.

The reel assembly must also be designed to maintain high voltage isolation of the tether from the Space Station ground in event of insulation failure on the tether.

- TENSION ALIGNMENT DEVICE
  - ALIGN TENSION VECTOR TO STATION CENTER-OF-MASS
  - ADEQUATE ALIGNMENT RANGE TO ACCOMMODATE STATION BUILD-UP, SHUTTLE DOCKING/DEPARTURE, AND TETHER ANGLE VARIATIONS (6^{o} HALF ANGLE CONE)
  - DESIGNED TO PROVIDE HIGH VOLTAGE ISOLATION IN EVENT OF TETHER INSULATION FAILURE
  - PROVIDE SERVICING BERTHING FOR END MASS SATELLITE
  - ACTIVE ALIGNMENT CONTROL BY STATION ATTITUDE CONTROL SYSTEM
- TETHER REEL AND DRIVE
  - REEL CAPACITY 31 KM OF SPECIFIED TETHER
  - ADEQUATELY POWERED TO PERFORM DEPLOY AND RETRIEVE OPERATIONS
  - DESIGNED TO PROVIDE HIGH VOLTAGE ISOLATION IN EVENT OF TETHER INSULATION FAILURE
  - HIGH POWER, HIGH VOLTAGE TERMINATION FOR TETHER CONNECTION TO HIGH VOLTAGE CONVERTER SYSTEM
  - MECHANICAL BRAKE SIZED TO HALT DEPLOY OR RETRIEVE PROCESS AT ANY POINT AND TO LOCK REEL AT FULL EXTENSION OF TETHER

(CONT'D)

Functional Requirements (Continued)

Dual Mode Converter

The performance requirements for the dual mode converter in each of the two operating modes are given.

- o DUAL MODE CONVERTER
  - HIGH VOLTAGE, HIGH POWER SYSTEM
  - GENERATOR MODE

    TETHER OUTPUT VOLTAGE RANGE ----------------------------4000 TO 5240V
    SOURCE IMPEDANCE (TETHER & PLASMA)-----------------------31 OHMS
    POWER OUTPUT TO STATION BUS----------------------------120 KW
    BUS VOLTAGE---140V
  - MOTOR MODE

    POWER TO TETHER--331 KW
    TETHER BACK EMF--4000 TO 5240V
    OUTPUT RANGE OF CONVERTER------------------------------7060 TO 8300V
    SOURCE POWER (STATION BUS)------------------------------140V
  - TARGET EFFICIENCY--90%
  - CAPABLE OF RAMPED SWITCHING FROM MODE TO MODE

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End Mass Satellite

This vehicle is designed to be a permanent part of Space Station that can be deployed for operations and retrieved for servicing and replenishment of consumables.

The conductive insulated tether, AWG #5, will require initial deployment and final retrieval tension in the 20 pound range to maintain a straight tether. Four, 5 pound thrust thrusters will accomplish this requirement. A mono propellant supply tank supplies the thrusters.

2 kWh of nicad rechargeable batteries will supply power to all vehicle support during transition intervals, and deployment/retrieval operations.

A DC/DC converter will condition electrodynamic power from the tether as required for satellite subsystems, and to keep the battery system charged.

A Ku band horn antenna and transceiver will provide the communications link to Space Station.

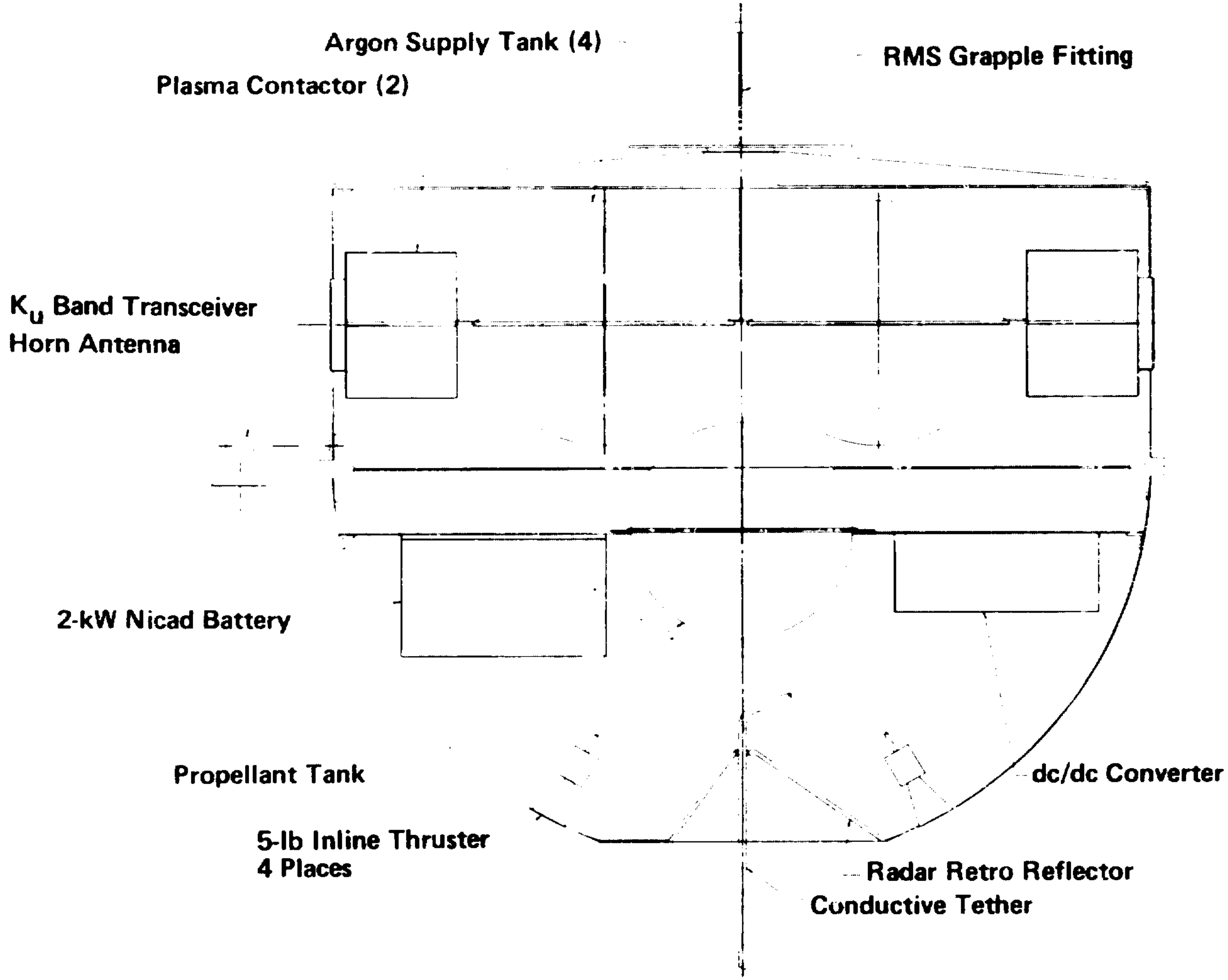
The radar reflector is used in conjunction with the Space Station radar system for tracking purposes.

Four, 3000 psi argon tanks are provided for six months plasma contactor operation. Section A-A shows the relative position of tanks and contactors in the top view. The layout is designed for EVA access to facilitate servicing operations.

The RMS grapple fitting will allow for shuttle retrieval in case of tether failure, or for RMS handling on the station.

The estimated mass of the end effector satellite as shown is 2350 lbm (kg). This includes 500 lbm of Argon gas and 240 lbm of propellant.

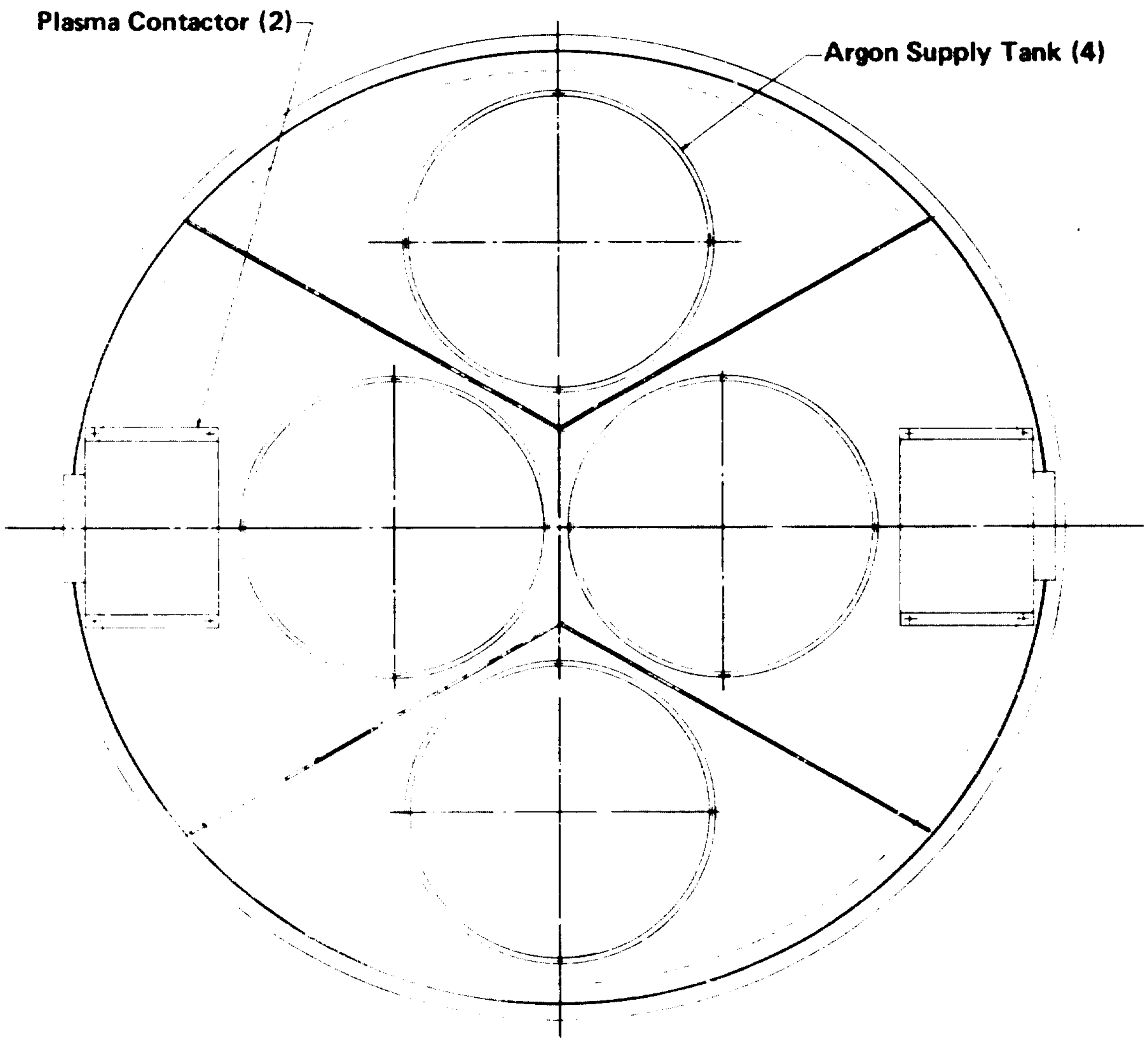
END MASS SATELLITE



End Mass Satellite - Section View

The same comments apply as for preceding chart.

END MASS SATELLITE - SECTION VIEW



Power Converter System

The design is based on the functional requirements (page E-7.3)

Based on the power conditioning requirements shown, several power converter topologies may be feasible. Several assumptions were made as a basis for the study:

- Control of tether dynamics will not require peak power beyond the steady state maximum power shown.
- Calculations were based on a twelve section power converter; ten are required for full power operation. Individual sections contain no redundant circuits.
- Any electronic power converter may be modulated with sufficient speed and power swing to accommodate the mechanical system.
- Radiation hardness beyond 10k rads is not a requirement.
- Tether characteristics would not produce extreme voltage or current surges.

The converter design shown is based on series resonant inverter topology.

Advantages:

- Long MTBF.
- No periodic maintenance required.
- No mechanical devices.
- Efficiency is high.
- With series resonant inverter topology, inherent EMI is lower due to freedom from harmonics and zero current switching.

Disadvantages:

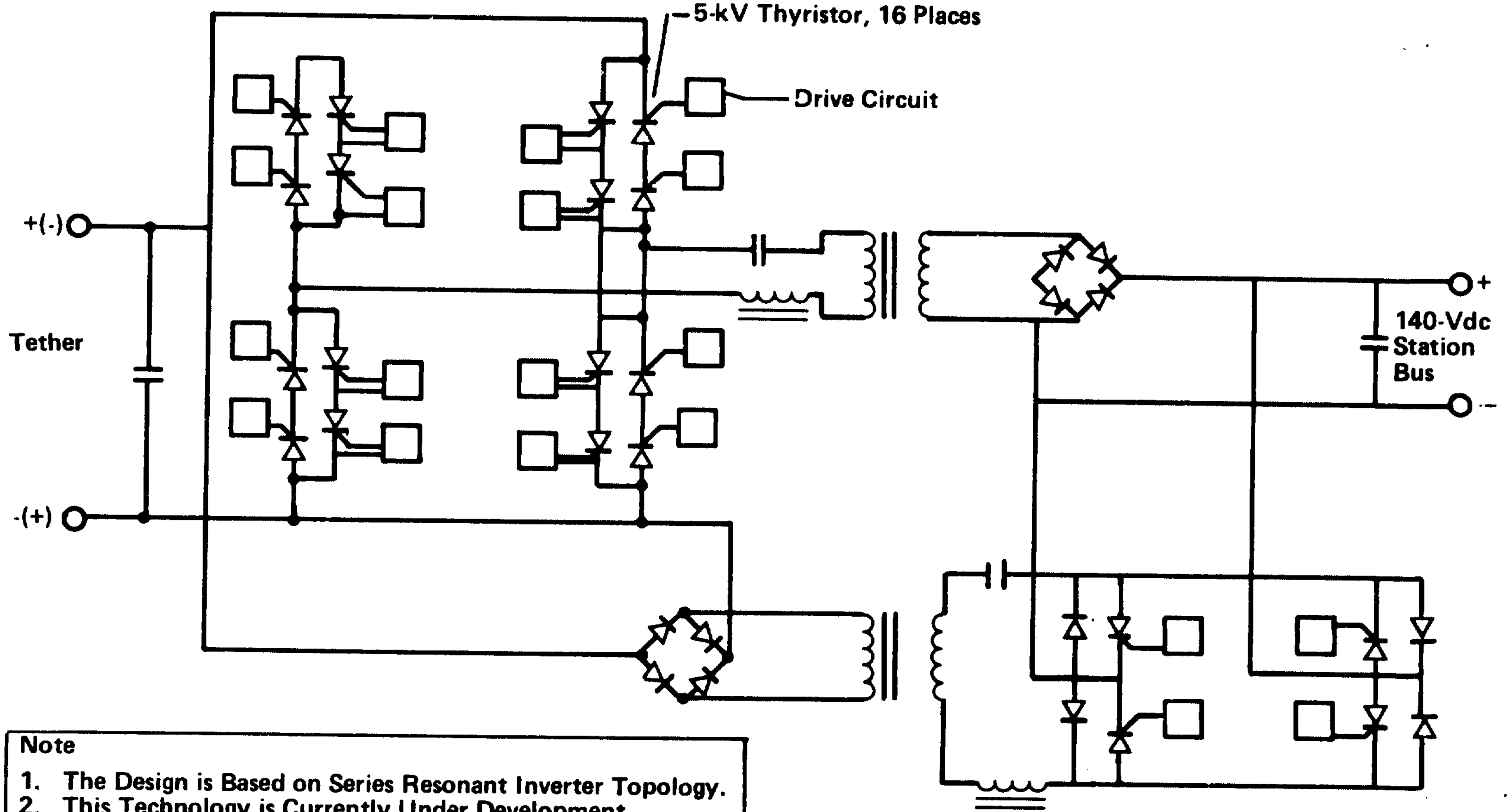
- The series resonant converter topology is still under development. A complete mathematical model has not yet been developed. Analysis capability is limited at this time.

System Sizing Estimates:

	Mass (kg)	Volume (m^3)	Power (kW)
Converter modules (each)	27.4	0.02	2.4
12 module system	329.	0.30	24.2 (10 each)
Radiator (area 58 m^2)	140.	-----	-----

Overall Efficiency: 94.% plus

Power Converter System



Note

1. The Design is Based on Series Resonant Inverter Topology.
2. This Technology is Currently Under Development.
3. One of 10 Modules is Shown. Each Will Process 12 kW in the Generator Mode and 33.1 kW in the Motor Mode.

Safety Considerations

1. In the event of a tether break - which could be due to a micrometeorite or space debris impact - there are two areas of concern. The first is a question of the disposition of the broken end severed from the Space Station. The second is the end mass satellite and its attached tether segment. Functional requirement provision has been made to jettison the tether from the satellite by means of a remote commandable guillotine. The satellite itself could then be retrieved by an OMV mission. The remaining areas of concern then would be the disposition of this outboard tether segment. The drag influenced orbit trajectories of these two tether segments need to be analyzed to assess hazard to the station or other vehicles.

2. In the event of a plasma contactor failure at either end of the tether, that end will no longer be in contact with the ambient plasma potential. Obviously the function of the tether as a drag or thrust generating device will cease. The affected end will be at the electrical potential dictated by the induced potential in the tether. This would present no problem for the outboard end. The station end would be of concern, however, as there would be a significant potential difference between the station and any approaching vehicles such as the Shuttle.

3. Breakdown of insulation anywhere in the high voltage termination of the tether at the station or the associated high voltage processing circuitry could cause arcing to station ground. The energy in this arc is primarily a function of the continued operation of the plasma contactors. If the plasma contactor function is inhibited the station potential should quickly rise to the tether potential suppressing the arc. These hypothesized processes need to be analyzed in more detail for hazards.

4. Any reel failure during either deploy or retrieve operations which cannot be repaired would result in a situation requiring jettison of the tether. The consequences are essentially the same as for item 1.

5. Thruster failure during the close-in stage of deploy or retrieve operations could result in a requirement for emergency jettison of the tether and end mass satellite. This again would result in a hazard situation similar to item 1.

6. The consequences of a malfunction of the tension alignment device could result in an effect on the attitude control capability of the station. Possible hazards from this consequence need to be analyzed.

SAFETY CONSIDERATIONS

1. TETHER BREAK.
2. PLASMA CONTACTOR FAILURE
   - STATION TERMINUS
   - END MASS TERMINUS
3. HIGH VOLTAGE SHORT TO STATION GROUND.
4. TETHER REEL FAILURE
   - DURING DEPLOYMENT
   - DURING RETRIEVAL
5. TETHER ALIGNED THRUSTER FAILURE
   - DEPLOYMENT
   - RETRIEVAL
6. TENSION ALIGNMENT DEVICE FAILURE.

Areas Needing Further Study

1. Performance characteristics of the ionosphere have not been addressed in this study. Obviously this is an area which needs much better understanding and experimental verification of predicted behavior.

2. The operational performance of plasma contactors are essential to the development of this concept. Better understanding of the operational characteristics of these devices is needed.

3. Selection of tether design is complex and depends on a variety of inter-related considerations. Examples are the selection of conductor material and fabrication, tether insulation - both for deployed sections and terminations, and thermal design considerations. An optimized combination of these considerations will require a significant further design study effort.

4. Design of the power converter devices for the system have some unusual requirements for which there is little design precedent. This includes both the high power converter for the station and the much lower power converter required to tap power from the tether to sustain the operation of the end mass satellite.

5. Tether dynamics for the electrodynamic tether introduce several new elements of complexity over those for non-conductive tethers. These new elements include:

   - The process of switching from the drag to the thrust mode and vice versa requires a better understanding of the associated transients and time required.

   - The integrated effects of the cross track component of the electrodynamic forces on tether dynamics.

   - The question of whether or not current modulation can be used to damp out the cross track libration needs to be addressed.

   - The close-in deploy and retrieve operations for the more massive and stiffer tethers needs further study.

AREAS NEEDING FURTHER STUDY

1. PERFORMANCE CHARACTERISTICS OF THE IONOSPHERE.
2. PLASMA CONTACTORS
   - PERFORMANCE CHARACTERISTICS
   - USAGE RATES FOR ION SOURCE GAS
3. TETHER DESIGN
   - OPTIMIZATION OF LENGTH, CONDUCTANCE
   - MATERIALS SELECTION
   - CONSTRUCTION
   - THERMAL CONTROL DESIGN
   - HIGH VOLTAGE TERMINATION AT STATION REEL END
4. POWER SYSTEMS
   - HIGH VOLTAGE DC/STATION BUS CONVERTER (DUAL MODE)
   - CURRENT MODULATION TECHNIQUES DURING MODE SWITCHING
   - END MASS SATELLITE POWER CONVERTER (DUAL MODE)
   - INSULATION DESIGN FOR HIGH VOLTAGE
5. TETHER DYNAMICS
   - MODE TRANSITIONS - TIME AND DYNAMICS
   - INTEGRATED EFFECTS OF OUT-OF-PLANE FORCES ON CROSS PLANE LIBRATIONS
   - CAPABILITY TO USE CURRENT MODULATION FOR LIBRATION DAMPING
   - CLOSE-IN DEPLOY AND RETRIEVE OPERATIONS

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Technology Development Needs

Areas in need of technology development for this concept are identified.

TECHNOLOGY DEVELOPMENT NEEDS

1. IONOSPHERE PERFORMANCE CHARACTERIZATION.
2. PLASMA CONTACTOR DESIGN AND PERFORMANCE CHARACTERIZATION.
3. HIGH VOLTAGE, HIGH POWER CONVERTER DESIGN.
4. HIGH POWER CONDUCTIVE TETHER DESIGN AND CONSTRUCTION.
5. HIGH POWER TETHER THERMAL DESIGN.
6. HIGH VOLTAGE INSULATION DESIGN FOR SPACE STATION TETHER TERMINUS.
7. DYNAMICS SIMULATION FOR ELECTRODYNAMIC TETHER.

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Alternative Concepts

The alternatives to this concept include a variety of energy storage systems that are under consideration for Space Station. Specifically this includes the following:

- o Nickel Cadmium batteries
- o Nickel Hydrogen batteries
- o Bipolar Nickel Hydrogen batteries
- o Regenerative Fuel Cell/Electrolizer systems
- o Inertial storage flywheel systems

An additional alternative is a nuclear reactor power system which does not require energy storage.

The primary area for comparison of this concept with the first group of alternatives is in the solar array power required to support the energy storage function. This will depend on the two way conversion efficiency of the process and on the integration time available to collect the solar energy required.

Other areas for comparison are:

- o Cost
- o Thermal Control
- o Operational Constraints
- o System Reliability
- o Maintenance Requirements
- o Logistics Support
- o Weight/Volume to Orbit

ALTERNATIVE CONCEPTS

- o BATTERY SYSTEMS
  - NICKEL CADMIUM
  - NICKEL HYDROGEN
  - BIPOLAR NICKEL HYDROGEN
- o REGENERATIVE FUEL CELLS
- o NUCLEAR REACTOR (NO ENERGY STORAGE REQUIRED)

<u>AREAS OF COMPARISON</u>

- o SOLAR ARRAY POWER (AREA) REQUIRED TO SUPPORT ENERGY STORAGE FUNCTION
  - TWO WAY CONVERSION EFFICIENCY
  - INTEGRATION TIME AVAILABLE
- o COST
- o HEAT REJECTION REQUIREMENTS
- o OPERATIONAL CONSTRAINTS
- o RELIABILITY
- o MAINTENANCE/LOGISTICS SUPPORT
- o WEIGHT/VOLUME TO ORBIT

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CONCLUSIONS

1. THERE ARE MANY CRUCIAL AREAS PERTAINING TO CONCEPT FEASIBILITY THAT ARE POORLY UNDERSTOOD.

   - IONOSPHERE CONDUCTIVITY CHARACTERIZATION
   - PLASMA CONTACTOR PERFORMANCE
   - TETHER DYNAMICS

2. NO FUNDAMENTAL REASON IDENTIFIED WHY SUCH A SYSTEM COULD NOT BE CONSTRUCTED.

3. USING STATED ASSUMPTIONS SEVERAL CONCERN AREAS HAVE BEEN IDENTIFIED.

   - MODE SWITCHING PROCESS
   - OUT OF PLANE FORCES ON TETHER
   - DYNAMICS OF ED TETHERS
   - SOLAR ARRAY REQUIREMENTS
   - NO GRACEFUL DEGRADATION
   - REQUIREMENT FOR CONVENTIONAL BACK-UP SYSTEM

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RECOMMENDATIONS

1. CONCEPT NOT READY FOR CONSIDERATION AS AN EARLY SPACE STATION STORAGE METHOD.
2. CONTINUE STUDY TO IMPROVE UNDERSTANDING AND UPGRADE FEASIBILITY STUDIES.
3. DEFINE SPECIFIC INVESTIGATIONS TO BE PERFORMED BY TSS PROGRAM TO ANSWER QUESTIONS.
4. EXPLORE FEASIBILITY OF SINGLE MODE APPLICATIONS.
    - THRUST MODE ONLY
    - DRAG MODE ONLY